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FLIGHT EVALUATION OF HL-10 LIFTING BODY HANDLING QUALITIES AT MACH NUMBERS FROM 0.30 TO 1.86

by Robert W. Kempel and John A. Manke

Flight Research Center
Edwards, Calif. 93523

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16. Abstract

The longitudinal and lateral-directional handling qualities of the HL-10 lifting body vehicle were evaluated in flight at Mach numbers up to 1.86 and altitudes up to approximately 27,450 meters (90,000 feet). In general, the vehicle's handling qualities were considered to be good. Approximately 91 percent of the pilot ratings were 3.5 or better, and 42.4 percent were 2.0.

Handling qualities problems were encountered during the first flight due to problems with the control system and vehicle aerodynamics. Modifications of the flight vehicle corrected all deficiencies, and no other significant handling qualities problems were encountered.

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INTRODUCTION

The National Aeronautics and Space Administration and the U.S. Air Force have jointly investigated the flight characteristics of several lifting body configurations to develop a reentry vehicle that can be maneuvered along a variety of entry paths. The first lifting body configuration tested in flight was the lightweight M2-F1 lifting body vehicle (ref. 1). After the M2-F1, the heavyweight M2-F2, HL-10, and X-24A lifting body configurations were flight tested at subsonic, transonic, and low supersonic speeds (ref. 2).

The primary objective of the HL-10's flight program was to assess the vehicle's longitudinal and lateral-directional handling qualities in the terminal portion of a reentry flight profile, including unpowered approach and landing. Control system and aerodynamic problems were encountered during the vehicle's first flight, so wind-tunnel studies and aerodynamic and control system modifications were made. During the 37 flights in the program, the HL-10 reached Mach numbers up to 1.86 and altitudes up to approximately 27,450 meters (90,000 feet).

This report discusses the HL-10's handling qualities in general and its longitudinal and lateral-directional handling qualities in detail. Pilot ratings of the vehicle's performance during specific tasks are given along with pilot comments. Flight-determined stability and control characteristics are compared with these pilot evaluations. A brief review of the vehicle's handling qualities during its first flight is also presented.

SYMBOLS

Physical quantities in this report are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. The measurements were taken in Customary Units. Factors relating the two systems are presented in reference 3.

a_n — normal acceleration, g units

a_y — lateral acceleration, g units

b — reference span, m (ft)

C_L	lift coefficient, $\frac{\text{Lift}}{\bar{q}S}$
C_{L_α}	lift-curve slope, $\frac{\partial C_L}{\partial \alpha}$, per deg
C_l	rolling moment coefficient
C_{l_β}	effective dihedral derivative, $\frac{\partial C_l}{\partial \beta}$, per deg
$C_{l_{\delta_a}}$	aileron effectiveness derivative, $\frac{\partial C_l}{\partial \delta_a}$, per deg
C_n	yawing moment coefficient, $\frac{\text{Yawing moment}}{qSb}$
C_{n_β}	directional stability derivative, $\frac{\partial C_n}{\partial \beta}$, per deg
$C_{n_{\delta_a}}$	yawing moment due to aileron deflection, $\frac{\partial C_n}{\partial \delta_n}$, per deg
$\bar{c}$	mean aerodynamic chord, m (ft)
g	acceleration due to gravity, 9.8 m/sec^2 (32.2 ft/sec^2)
h	altitude, m (ft)
I_X, I_Y, I_Z	vehicle moments of inertia about the X-, Y-, and Z-body axes, kg-m^2 (slug-ft^2)
I_{XZ}	product of inertia, kg-m^2 (slug-ft^2)
K_p	roll damper gain, deg/deg/sec
K_q	pitch damper gain, deg/deg/sec
K_r	yaw damper gain, deg/deg/sec
L_{δ_a}	dimensionalized aileron effectiveness derivative, per sec^2
M	Mach number

m	mass, kg (slugs)
p	rolling angular rate, deg/sec
q	pitching angular rate, deg/sec
$\bar{q}$	dynamic pressure, N/m^2 (lb/ft^2)
r	yawing angular rate, deg/sec
S	reference planform area, m^2 (ft^2)
t	time, sec
V	true airspeed, m/sec (ft/sec)
x, y, z	vehicle forward, transverse, and vertical body axis coordinates
α	angle of attack, deg or rad
β	angle of sideslip, deg
δ_a	aileron deflection, deg
$\delta_{a_{max}}$	maximum possible aileron deflection, deg
δ_e	elevon deflection, deg
δ_{ef}	elevon flap deflection, deg
δ_{es}	longitudinal stick deflection, cm (in.)
δ_{ls}	lateral stick deflection, cm (in.)
δ_r	rudder deflection, deg
δ_{rp}	rudder pedal deflection, cm (in.)
ϵ	inclination of principal axis, deg
ζ_d	Dutch-roll mode damping ratio
ζ_{sp}	longitudinal short-period mode damping ratio
θ	angle of pitch, deg

τ_r	roll mode time constant, sec
τ_{sp_1}	first short-period mode time constant, sec
τ_{sp_2}	second short-period mode time constant, sec
φ	angle of bank, deg
$\lvert\varphi/\beta\rvert_d$	bank-angle-to-sideslip-angle ratio of the Dutch-roll mode
ω_d	Dutch-roll mode frequency, rad/sec
ω_{sp}	longitudinal short-period mode frequency, rad/sec or Hz

VEHICLE DESCRIPTION

The HL-10 lifting body (figs. 1(a) and 1(b)) is a single-place vehicle with a relatively conventional fighter aircraft cockpit and instrument panel (fig. 2). The vehicle is a negatively cambered airfoil with a 74° sweptback delta planform with three aft vertical fins. The dimensions and physical characteristics of the vehicle are presented in table 1 and figure 1(b).

Aerodynamic control was provided by the elevons and rudder. The elevons provided pitch and roll control, damping augmentation, and trim. The split rudder, which was located on the center vertical fin, operated as both rudder and speed brake.

Secondary control surfaces were located on the inboard and outboard trailing edges of the tip fins and the upper surface of the elevons. These surfaces, which were deploye by electric motors, were two-position flaps that closed for the subsonic configuration (fig. 3(a)) and opened for the transonic configuration (fig. 3(b)). Table 2 compares the secondary control flap positions for the subsonic and transonic configurations. The subsonic flap positions were changed after the second flight because the results of the flight indicated that the elevon deflection required for trim in flight and in the wind tunnel differed. Data for an in-flight trim condition with an elevon flap deflection of 5° closely approximated wind-tunnel data for 0° of elevon flap.

The primary control surfaces, which were actuated by an irreversible hydraulic system, accepted commands from the pilot and the stability augmentation system (SAS). The authority of the SAS was ±5° in roll, pitch, and yaw. The authorities of the pilot's stick and rudder pedal and the corresponding control surfaces are presented in table 3. The pilot was provided with stick and rudder pedal force feel by coil-spring bungees, which provided a force proportional to stick or rudder pedal position. The changes in the authority and gearing of the pilot's controls (table 3) resulted from pilot evaluations and flight trim data.

The limited-authority rate feedback SAS (fig. 4) provided damping augmentation about all three axes. The feedback signals were provided by conventional rate gyros. The pilot selected SAS gains ranging from 0 to 1.0 in increments of 0.1 in terms of degrees of surface deflection per degree per second of angular rate. The gains were fixed unless the pilot changed the position of the SAS control switch, which was on the left console. The yaw rate signal was modified by an electronic high pass filter (washout filter) so that the rudder returned to zero deflection as the yaw rate approached steady state. This kept constant rate turns from being impeded.

The instrument display included indicators of airspeed, altitude, angle of attack, normal acceleration, and control surface position. A three-axis attitude indicator (fig. 2) provided attitude and sideslip information. (The landing gear was actuated by a lever to the left of the instrument panel.) The landing gear was pneumatically actuated, and its extension took approximately 1 second.

INSTRUMENTATION

The data were acquired by means of a pulse code modulation telemetry system and were recorded digitally on magnetic tape at the ground station. Two hundred samples per second were taken. The data were estimated to be accurate within 2 percent; accuracies are given in greater detail in reference 4.

FLIGHT TESTS

Flight Envelope

The approximate operational flight envelope of the HL-10 is shown in figure 5 in terms of altitude and Mach number. The flight envelope was bounded at the bottom by the dynamic pressure structural limit (191.5 kN/m^2 (400 lb/ft^2)) and at the top by the minimum control effectiveness.

Flight Test Methods

The HL-10 was launched from a B-52 airplane at an altitude of approximately 13,720 meters (45,000 feet) and a Mach number of 0.65. A series of glide flights preceded the powered flights so that the vehicle's aerodynamics and systems could be evaluated and the pilots could be checked out. Table 4 summarizes the 37 HL-10 flights in terms of the type of flight and the maximum Mach number and altitude reached during each flight. Figure 6 shows the ground tracks of the flights in the terminal approach and landing pattern. The launch point for the powered flights was left of the glide flight launch point by approximately 74.08 kilometers (40 nautical miles). The point labeled runway intersection was the intersection of runways 4 and 17 at Edwards Air Force Base and was the point where the vehicle normally changed from the transonic to the subsonic configuration. During a flight, ground radar tracked the HL-10 and provided mission control with ground track and altitude information. Deviations from the planned profile because of such factors as high or low energy were radioed to the pilot for corrective action. The low key point on the ground track occurred at an altitude of approximately 6100 meters (20,000 feet). Geographical positioning at the intersection differed from flight to flight depending on energy level; however, the low key point was intersected consistently. A 180° turn was then made to the final approach and landing.

A typical glide flight began with launch of the HL-10 in the transonic configuration. The vehicle's controllability was evaluated in this configuration. This evaluation was followed by a configuration change and visual navigation to the downwind leg where another vehicle evaluation was performed. The vehicle was then turned to the base leg, and the final approach, flare, and landing were made. The average flight time was 4.2 minutes.

A typical powered flight also began with launch in the transonic configuration. Immediately after launch, the vehicle was rotated to an angle of attack of 23° as its engine was ignited. Vehicle rotation then continued to a pitch attitude of approximately 50°. The vehicle climbed to an altitude of 16,150 meters (53,000 feet) where it was pushed over to 0.3g and then accelerated to Mach 1.36. This was followed by the burnout of the rocket engine and the initiation of data acquisition. Data were acquired at specified Mach numbers and angles of attack. Subsequently, the vehicle changed to the subsonic configuration and intersected the glide flight ground track. The remainder of the flight was the same as for a glide flight. The average powered flight time was approximately 6.7 minutes, and the usual rocket engine burn time was 1.5 minutes.

During one flight, an early rocket engine shutdown caused a low-energy situation. The pilot looked outside the cockpit and reported that he thought he had excess energy; however, he was actually considerably below the profile. The pilot also reported that it was easy to return to the planned flight profile from the low-energy condition prior to reaching the low key point. The pilot commented that once outside the pattern something other than visual reference was needed to assess the energy situation. In the pattern the pilots could estimate energy well, however.

PILOT RATINGS AND RATING SCALES

To assess the in-flight handling qualities of the HL-10, the pilots were asked to evaluate certain maneuvers and tasks at specified angles of attack and Mach numbers. Some of the tasks were part of the flight profile, such as the powered boost, turns, and flare. Narrative and numerical evaluations of the vehicle's handling qualities and response characteristics were obtained immediately after each flight. The numerical ratings were based on a modified Cooper-Harper scale (ref. 5). Evaluations based on the flying qualities specification currently in use by military organizations for piloted aircraft (ref. 6) were also made. For the latter evaluation the HL-10 was considered a Class II vehicle — a mediumweight aircraft with low to medium maneuverability. The flight phases considered to be applicable were nonterminal (category B) and terminal (category C). The nonterminal flight phase was defined as nonterminal flight that is normally accompanied by gradual maneuvers without precision tracking, although a requirement for accurate flightpath control may exist. A terminal flight phase was defined as terminal flight, which normally consists of gradual maneuvers that require accurate flightpath control.

Table 5 presents the scale of handling qualities used throughout the flight program and the corresponding levels of flying qualities from the Military Specification.

DISCUSSION

General Handling Qualities

Overall stability and control. - The five program pilots gave 419 pilot ratings during the 37 flights in the program. Figure 7 presents a percentage distribution of all the ratings. The figure shows that the most frequent pilot rating was 2.0; this rating constituted 42.4 percent of those obtained. Less than 10 percent of the ratings ranged from 4.0 to 6.0 (only two ratings of 6.0 were assigned). Approximately 91 percent of the ratings were 3.5 or better.

Figures 8 and 9 present percentage distributions of the pilot ratings of the longitudinal and lateral-directional axes, respectively. SAS-on and -off data are combined. The vehicle's longitudinal handling qualities were moderately affected by configuration; 93.3 percent of the ratings were 3.5 or better for the subsonic configuration, and 88.1 percent of the ratings were 3.5 or better for the transonic configuration. The ratings of the lateral-directional characteristics of the subsonic configuration were markedly better than those of the transonic configuration; 95.9 percent of the subsonic configuration ratings were 3.5 or better, whereas 77.1 percent of the transonic configuration ratings were 3.5 or better.

Ten percent of the total pilot ratings were for SAS-off conditions. The handling qualities of the HL-10 under these conditions were considered to be good. After considerable maneuvering and numerous flap changes, the pilot ratings remained in the 4.0 to 5.0 range. All the pilots felt that the vehicle was completely flyable with the SAS off and that a mission could be completed successfully. Typical pilot comments indicated that with the SAS off the vehicle had high roll control sensitivity and surprisingly good pitch damping. The pilots also commented that with the SAS off the HL-10 handled better than an F-104 airplane with the dampers off.

Although the vehicle's SAS-on handling qualities were generally considered to be good, SAS-on handling qualities and stability problems did occur in some portions of the flight envelope. The flight envelope is indicated in figure 10, which shows the angle of attack and Mach number range of the HL-10. The vehicle usually operated between zero lift ($\alpha = 4^\circ$ to 6°) and maximum lift-to-drag ratio ($\alpha = 16^\circ$ to 20°). The hashed area in the lower left of the figure shows where high pitch sensitivity caused handling problems. The hashed area at the upper right shows where the roll SAS induced a Dutch-roll mode instability.

Postlaunch powered boost. - The postlaunch task was rated between 2.0 and 3.0 for both powered and glide flights. The longitudinal control task was more difficult during powered flight because the rocket engine had to be started, the SAS switches had to be changed, and a specific angle of attack and pitch attitude had to be attained shortly after launch so that the desired Mach number and altitude conditions could be reached. The pitch attitude angle was typically 55° to 60°, and the angle of attack was typically 23° to 28°. Pilot ratings of the vehicle's longitudinal handling qualities during this task were typically 2.5. The lateral-directional handling qualities were less satisfactory, with typical ratings of 3.0.

Typical pilot comments concerning the postlaunch task were as follows:

> I seemed to get a little more rolloff during launch on this flight than on the last one. I used the same longitudinal control technique on this flight as on the last one, that is, I utilized trim only to get to 20° angle of attack, with no manual stick inputs. This makes a very smooth transition between launch trim and the desired angle of attack. The same technique was used to maintain the desired pitch attitude. I would rate this longitudinal task a 2.0.
>
> Prior to reaching 41° pitch attitude, [mission control] requested a 5° heading change to the right. The turn was initiated at 20° angle of attack and approximately 35° pitch attitude. I was pleasantly surprised at the ease with which the task was accomplished. The aircraft response to the turn input was very positive and rapid. I would rate the lateral controllability a 3.0.
>
> The overall postlaunch task is a busy one at best, but its difficulty is minimized because of the excellent stability of the aircraft. Also, previous simulator practice is indispensable in establishing motion patterns to accomplish the task in minimum time. The overall task was rated a 2.0.

On the first powered flight the rocket engine failed to ignite, and an alternate flight plan was immediately put into effect. The pilot reported that the launch was mild but that he had trouble getting his hand to the SAS switches. When he did, he reported that the switches seemed to operate differently from those in the simulator. When the switches were set, an attempt to ignite two chambers of the rocket engine failed. This was followed by a check of angle of attack. (The flight plan called for 16° of angle of attack on rotation.) The pilot reported that the angle of attack was 22° and that this confirmed his suspicion that it would be easy to overrotate. He rated his ability to stabilize on the desired angle of attack 6.0 and his ability to accomplish overall recovery after launch 5.0. He added that these ratings were assigned because of the high pilot work load.

Final approach, flare, and landing.- Lifting body landing procedures and rationale are described in detail in reference 7.

The pilots considered the HL-10 to have generally good handling qualities in the final approach, flare, and landing. Of the pilot ratings for this task, 96 percent were 3.5 or better. Two objectionable characteristics in this portion of the flight profile were nose window distortion and overly sensitive longitudinal stick characteristics.

In general, the Plexiglas nose window provided good forward vision for navigation and maneuvering. However, the window was lenticular in shape and therefore caused great visual distortion. In the landing approach just before the deployment of the landing gear, this distortion gave the pilots the impression that they were higher than they were. As a result, on their first flight some of the pilots waited until they were critically low before extending the landing gear. This problem disappeared as the pilots gained experience. One pilot reported that touchdown occurred before he expected it (at approximately 205 knots indicated airspeed) because of nose window distortion.

Another pilot commented that the visual distortion of the nose window was a significant problem and probably the vehicle's greatest shortcoming.

Longitudinal Handling Qualities

Longitudinal stick gearing. - Preliminary wind-tunnel data indicated that approximately 60° of elevon travel would be necessary to trim the HL-10 throughout the flight envelope.

The total longitudinal stick authority was approximately 22.9 centimeters (9 inches) measured at the pilot's grip (table 3). Figure 11 is a plot of elevon position as a function of stick position. The gearing for the first flight was approximately 2.73 degrees of elevon per centimeter (6.9 degrees per inch) of stick deflection, so landing required a stick deflection of only 2.5 centimeters (1 inch). This was much too sensitive. In addition, the subsonic configuration generally trimmed in the negative elevon range and the transonic configuration in the positive elevon range. Therefore an interim gearing was incorporated for the investigation of the vehicle's subsonic flight trim characteristics with the intent of adding a series trimmer for the transonic portion of the test program.

The interim gearing selected was 1.27 degrees of elevon per centimeter (3.24 degrees per inch) of stick, so approximately 5.9 centimeters (2.3 inches) of longitudinal stick deflection were used at landing. Although the vehicle was still too sensitive during flare and landing, the interim gearing was considered to be acceptable. Flight results and wind-tunnel data indicated that maximum positive elevon deflection requirements would not exceed 14°.

A final nonlinear gearing was incorporated which provided higher gearing at the higher positive elevon settings and lower gearing in the approach and landing settings. With this gearing, the stick was deflected approximately 5.1 centimeters (2 inches) during approach and landing. This was considered sensitive but acceptable. One pilot reported that the only reason he would not want to land with the pitch damper off was that without the damper the vehicle tended toward longitudinal pilot-induced oscillations.

Longitudinal trim. - Before the HL-10 was flight tested, a large trim change was expected to result from making the transition from the transonic to the subsonic configuration. Simulator studies indicated that large angle of attack and normal acceleration excursions would occur because of the large change in longitudinal stick position. The studies also indicated that the best technique would be to change configuration in steps. However, the flight tests showed that maintaining a constant angle of attack during the configuration change was not a problem (fig. 12). The pilot was able to maintain a nearly constant angle of attack in the 5 seconds it took to reconfigure the vehicle despite a large change in longitudinal stick position. It was also found that the best way to change configuration was in one continuous motion. This maneuver was assigned a pilot rating of 2.0. Before the flight-test program was completed, the configuration transition was also made with the pitch damper off. Pilot comments regarding one of the transition maneuvers were as follows: "The configuration change with $K_q = 0$ [zero pitch damper gain] was a pleasant surprise. It presented no problem. I would rate it 4.0."

A trim change that did cause some difficulty was associated with the vehicle's center-of-pressure shift during deceleration from Mach 0.97 to Mach 0.96. Wind-tunnel and simulation data indicated that the transonic trim change would occur from Mach 0.95 to Mach 1.0 but that this region would be traversed slowly enough so that it would present no piloting problem. In flight, however, deceleration through this Mach number range was rapid enough so that the trim change felt like a constant speed pitchup to the pilot. Figure 13 is a time history of a transonic trim change. This transient was rated 5.0 by the pilot because of the high rate of onset and his unfamiliarity with the phenomenon. The transient lasted less than 2.5 seconds. Later it was found that traversing this region at a lower angle of attack minimized the pitchup. In addition, since the time of onset could be predicted accurately, the pitchup did not come as a surprise on the later flights. This region was eventually traversed with the pitch damper off without difficulty. Under power, the vehicle accelerated through the 0.96 to 0.97 Mach number range comparatively slowly, so that this trim change occurred at a much lower rate than in the glide flights. Thus it presented no significant piloting problem.

No objectionable trim changes were caused by rocket engine ignition, engine shutdown, speed brake deployment, or landing gear extension.

Longitudinal stability and control. - Early wind-tunnel tests indicated that the HL-10 displayed a marked decrease in longitudinal static stability as it approached transonic speed because of the severely boat-tailed afterbody. The two-position flap concept was developed to solve this problem. Extending the flaps to the transonic position preserved the vehicle's static longitudinal stability but reduced its maximum lift-to-drag ratio by approximately 0.9. With the two-position flaps, the longitudinal stability of the HL-10 was satisfactory throughout its flight envelope.

Longitudinal damping without the pitch SAS was low throughout the flight envelope. The low damping combined with the sensitivity of the longitudinal stick gearing to make the vehicle overly sensitive, and this sensitivity was the subject of many pilot comments. However, the pilots also reported that the flight vehicle was better damped than the simulator.

Figure 14 shows the HL-10's longitudinal short-period natural frequency as a function of damping ratio in terms of the criteria proposed in references 6 and 8. Table 6 lists the task, configuration, pilot ratings, flight conditions, and response characteristics for these longitudinal data. The flight data point at $\zeta_{sp} = 0.134$ was given a pilot rating of 5.0. The pilot's comments were as follows:

> The residual oscillations after the pitch pulse indicated that the aircraft was better than the simulator [i.e., predictions]. I would estimate the aircraft to have been twice as well damped as the simulator. The behavior of the aircraft with the pitch damper off was a pleasant surprise. There is no question that it was quite sensitive in pitch and that damping was rather low, but it was absolutely flyable, particularly if the maneuvers were performed utilizing trim only.

Even though the pitch damping was low with the SAS off, with the SAS on the damping was well within the 3.5 pilot rating boundary of reference 8, as shown by the hashed areas at $K_q = 0.1$ and $K_q = 0.2$. The rating of 4.0 within the 3.5 boundary was given because of a lack of forward trim at low angles of attack rather than a lack of stability or damping. The rating of 2.5 at $\zeta_{sp} = 0.2$ was given after a very limited evaluation at a high Mach number.

The data points in figure 14 are compared with the current Military Specification requirements (ref. 6) for short-period frequency and acceleration sensitivity in figure 15. The HL-10's short-period mode frequency and acceleration sensitivity characteristics were generally considered to be satisfactory. The transonic configuration data are generally between levels 1 and 2, and the data point for the subsonic configuration is in the region for level 1. The landing approach data, indicated by the hashed area, are also within the level 1 region.

Lateral-Directional Handling Qualities

Lateral stick gearing.- The HL-10 was designed to provide a maximum aileron deflection of $\pm 40^\circ$. The maximum design pilot aileron authority was $\pm 20^\circ$ at approximately ± 7.6 centimeters (approximately ± 3 inches) of lateral stick deflection (table 3). The SAS design maximum aileron authority was also $\pm 20^\circ$. An acceptable level of SAS aileron authority was determined to be $\pm 5^\circ$. Before flight, two levels of lateral stick gearing were selected for detailed evaluation: 1.68 degrees per centimeter (4.27 degrees per inch) and 2.86 degrees per centimeter (7.25 degrees per inch); the pilot's aileron authority was $\pm 12.5^\circ$ and $\pm 19.2^\circ$, respectively. To obtain these gearings the lateral stick deflection of ± 7.44 centimeters (± 2.93 inches) was retained.

Flight and simulator results indicated that the lower aileron gearing (1.68 degrees per centimeter (4.27 degrees per inch)) provided the pilot with the desired level of stick sensitivity. These results also indicated a need for higher pilot aileron authority (higher control power). To combine lower gearing with high authority, a modification was made after flight 9 (table 3) that increased the pilot's lateral stick displacement. The final maximum pilot's lateral stick displacement was ± 10.29 centimeters (± 4.05 inches) at a gearing of 1.68 degrees per centimeter (4.27 degrees per inch) and a total aileron deflection of $\pm 17.3^\circ$.

Lateral-directional trim.- The original design specifications for the HL-10 called for pitch and yaw trim capability but no in-flight roll trim capability. After the first few flights, however, many complaints were made about the lack of lateral trim. One pilot said, ". . . ability to control bank angle was good and lateral control sensitivity was also good, and I would give [this task] a pilot rating of 2.0, but [shall] give it a pilot rating of 5.0 because of the lack of lateral trimmability." After flight 9 the capability for in-flight pilot adjustment of lateral trim was provided, and no other comments were made.

Lateral-directional stability and control.- The lateral-directional aerodynamic stability characteristics of the HL-10, like those of all lifting body configurations, were dominated by high effective dihedral, C_{l_β} (ref. 9). The vehicle's directional stability was generally adequate throughout the flight envelope, although the derivative, C_{n_β}, varied considerably with Mach number and angle of attack.

The control effectiveness of the HL-10 was generally satisfactory throughout the flight envelope for both control and damping augmentation. The aileron control effectiveness was particularly good in comparison with that of the other lifting body configurations. The rolling moment effectiveness remained high throughout the Mach number and angle of attack flight region, and the vehicle's aileron yawing moment characteristics were generally proverse or favorable.

The HL-10's Dutch-roll mode damping without the roll or yaw SAS was low. Figure 16 compares the HL-10's Dutch-roll mode frequency and damping ratio characteristics with the current Military Specification for piloted airplanes (ref. 6). Table 7 presents the task, configuration, pilot ratings, flight conditions, and response characteristics for these lateral-directional data. The vehicle's high effective dihedral contributed to the high frequency characteristics of the Dutch-roll mode, which ranged from 2.9 to 6.4 radians per second. With the roll and yaw SAS off, the data are below the boundary for level 2 handling qualities, and the vehicle was given pilot ratings from 4.5 to 6.0. The roll SAS-off data are all below the boundary for level 1 handling qualities, and most are between the boundaries for level 1 and 2 handling qualities. Pilot ratings of the vehicle with the roll SAS off ranged from 2.0 to 4.5. With the roll and yaw SAS on, the damping generally exceeded the level 1 requirements. The only data point below the level 1 boundary was obtained at a low dynamic pressure and low roll and yaw SAS gains.

The SAS-on Dutch-roll mode damping was generally satisfactory. However, on three occasions a SAS-on Dutch-roll mode divergent oscillation was experienced. These divergences occurred at a Mach number of approximately 1.3 and an angle of attack of 24° (fig. 10). Figure 17 shows that a rudder pulse was the initial excitation and that a sinusoidal divergence resulted. Flight-determined data from reference 9 indicated that the rolling moment effectiveness was lower than predicted at these flight conditions and that the yawing moment effectiveness and the effective dihedral were higher than predicted. Root-locus analysis using flight data indicated that the roll SAS drove the Dutch-roll mode unstable and that the vehicle was stable with the roll SAS off. The time to double amplitude was approximately 9 seconds, and the incident did not seriously disturb the pilot. Recovery was effected by decreasing the angle of attack. The pilot reported that as soon as he pulsed the rudder pedal he could feel the oscillation diverging at a slow rate and that as soon as he decreased the angle of attack the oscillation damped out.

The HL-10's roll mode response without the roll SAS was characterized by roll mode time constants between 1 and 10 seconds. The ailerons, working through the SAS, augmented roll mode damping effectively, however. The SAS-on roll mode time constants were between 0.1 and 1.0 second. The combination of low roll mode damping (large time constants) and high effective dihedral made other lifting body configurations susceptible to roll-spiral mode coupling (ref. 10), but the HL-10 with the SAS on did not exhibit roll-spiral mode characteristics. Figure 18 presents pilot ratings as a function of roll mode time constant as compared with the Military Specification (ref. 6) and data from reference 11. These data are also presented in table 7. In general, the ratings are below the reference 11 boundary, except for the ratings given by pilot 1, who rated the vehicle better than the other pilots. This difference in ratings may be a result of the fact that pilot 1 rated a $\pm 20^{\circ}$ bank angle task and the other pilots rated a stability and control task. In addition, the flight tasks were all in six degrees of freedom, while the criteria from reference 11 were for studies for only three degrees of freedom. The flight ratings are in relatively good agreement with the criterion of reference 6 at roll mode time constants less than 3 seconds. Above roll mode time constants of 3 seconds, the vehicle was rated better than the criterion would indicate.

Pilot comments for the data points at τ_r = 0.74, 1.56, and 2.70 seconds (table 7) indicated that the dominant handling qualities characteristic rated was roll response. The pilot comments were as follows:

> Three combinations of lateral-directional SAS setting were flown. The task in each case was a lateral-directional pulse followed by a roll control evaluation. In all cases the increased roll sensitivity was the dominant factor, and the three cases varied only in regard to roll sensitivity. [All three cases were with roll SAS off.] The first condition [τ_r = 1.56 seconds] was at a yaw SAS gain of 0.2, and I would rate this condition 4.0. The second condition [τ_r = 2.70 seconds] was with the yaw SAS off. Although it was extremely sensitive in roll, it was very flyable. I am convinced that a total roll and yaw SAS failure would not be catastrophic. The aircraft seems to be the most sensitive near zero aileron. As larger amounts of aileron were used, the sensitivity near the trimmed condition makes one initially quite reluctant to do much lateral maneuvering, but after this flight I am convinced that the airplane is quite honest with both dampers off. I would rate this condition a 5.0. The third condition [τ_r = 0.74 second] was at a yaw gain of 0.4. This is the gain we would use in the event of a roll SAS failure. This was definitely the best of the three conditions. The higher yaw gain was very effective in reducing the apparent roll sensitivity. I would rate this condition 3.5.

Figure 19, a plot of aileron control power as a function of roll mode time constant, compares pilot iso-opinion contours from reference 12 with HL-10 flight data. The contours were obtained from fixed- and moving-base single-degree-of-freedom roll mode studies for fighter aircraft, with in-flight verification. At time constants above 1 second, agreement is good, while at time constants less than 1 second the agreement is relatively poor. However, the in-flight task was never single axis and other dynamic modes were present. The significant evaluation, at roll mode time constants above 1 second, considered only the rolling characteristics.

Turbulence response. - Low altitude turbulence was present in the landing approach pattern anywhere from approximately 3970 meters (13,000 feet) to touchdown. The dominant response of the HL-10 to turbulence was in the form of low-amplitude, high-frequency roll accelerations with changes in bank angle of 2° to 3°. This response was due to sideslip disturbances and the excessively high effective dihedral. Normal force disturbances were less noticeable because of the low lift-curve slope (untrimmed $C_{L_\alpha} \approx 0.035$ per deg).

This type of response to turbulence was different from anything the pilots had experienced in winged aircraft, and early in the flight-test program they were apprehensive about flying through turbulence. Their anxiety diminished after several flights through turbulence showed that the vehicle handled well and that the disturbances damped out. Pilot apprehension was further reduced by flying a transport airplane through the HL-10's corridor a few minutes before the HL-10 flight and informing the HL-10 pilot of the location and severity of the turbulence.

First Flight Handling Qualities

The first flight of the HL-10, a glide flight, was different from the following 36 flights in that three serious problems were encountered: objectionable pitch control system limit cycles, overly sensitive longitudinal stick gearing, and aerodynamic flow separation over the upper aft portion of the vehicle. Immediately after the HL-10 was launched, the pilot became aware of the longitudinal control system limit cycle and the oversensitivity of the longitudinal control stick. These problems persisted throughout the 188-second flight, with the limit cycle becoming severe toward the latter portion of the flight (fig. 20). Eight SAS gain changes were made during the flight; the pitch SAS settings decreased from 0.6 to 0.2 before touchdown. The severe limit cycle persisted even after the reduction in SAS gain.

The third problem, an apparently low level of roll control power, was reported by the pilot to be only a "confusion factor." Accordingly, he rated the lateral-directional handling qualities from 1.0 to 3.5. Analysis of the flight data, however, revealed the potential seriousness of the problem and showed that it was caused, in part, by intermittent separation of the flow field over the upper aft portions of the vehicle. Figure 21 illustrates the flow separation and its effects on the vehicle's lateral-directional respon characteristics. The separated flow and the transition between separated and attached flow is best illustrated by the tip fin flap strain-gage responses. These show a wide band high-frequency disturbance when the flow is separated and a relatively thin, undisturbed trace when the flow is attached. The effect of the flow characteristics on vehicle motion is illustrated by a comparison of the pilot's aileron input with bank angle and roll rate. As the flow became attached, a rapid bank angle change and a large roll rate was generated in response to existing aileron inputs and sideslip angle ($t \approx 12.8$ sec and 45.0 sec). When the flow was separated, however, large aileron inputs resulted in slight or no vehicle response ($t \approx 0$ sec to 12.8 sec and 20 sec to 45 sec). The rudder was effective enough to produce sideslip when the flow was separated. The flow became attached as angle of attack decreased below approximately 5°. At $t > 45$ seconds, Mach number decreased enough to prevent the Mach number-angle of attack separation (buffet) boundary from being crossed again. From that point on, the controls functioned normally.

As a result of the flow separation problem, additional wind-tunnel tests were conducted to identify the portion of the vehicle where separation occurred and the aerodynamic modification to correct it. The wind-tunnel tests (refs. 13 and 14) revealed that the separation occurred near the tip fin leading edge and fin/body juncture and became more severe as it moved aft over the upper surface of the vehicle. As a result of these tests, the leading edges of the tip fins were extended and cambered to improve the aerodynamic flow over the vehicle. In addition, the longitudinal stick gearing was reduced, and the control system was modified. The flight-test program was resumed, and no other problems due to flow separation or control system malfunctions arose.

CONCLUDING REMARKS

A flight study to assess the longitudinal and lateral-directional handling qualities of the HL-10 lifting body vehicle indicated that the vehicle's handling qualities were generally satisfactory. Approximately 91 percent of the pilot ratings were 3.5 or better 42.4 percent were 2.0, the rating most frequently assigned, indicating that the handling qualities were good; and less than 10 percent were from 4.0 to 6.0.

The pilots found the powered postlaunch task work load to be high, but the vehicle's handling characteristics were good. This task was typically rated 2.5.

The final approach, flare, and landing characteristics were considered to be good; 96 percent of the pilot ratings were 3.5 or better. The longitudinal stick gearing was oversensitive, but after several changes to decrease the sensitivity, nonlinear gearing was incorporated successfully. Also, the nose window caused visual distortion.

A longitudinal pitchup trim change during deceleration past a Mach number of approximately 1 caused some handling qualities problems at first because of its abruptness. When the pilots had more experience, they anticipated this trim change and had no problems with it. No other major trim changes were experienced.

Longitudinal short-period mode dynamics were generally satisfactory with pitch stability augmentation. Without the augmentation, longitudinal damping was low. The vehicle's acceleration sensitivity parameter characteristics were generally satisfactory.

Lateral stick gearing and aileron authority required changes to provide the required sensitivity and control power.

In-flight lateral trim capability was provided in response to frequent complaints by the pilots.

Lateral-directional stability was dominated by the high effective dihedral typical of lifting bodies. Aileron control effectiveness was particularly good compared with that of other lifting bodies. The ailerons provided good roll damping (through the roll stability augmentation system) and roll control (because of the ailerons' favorable or proverse yawing moment characteristics). The Dutch-roll mode dynamic characteristics were generally satisfactory, although the damping with roll and yaw stability augmentation off was light. A divergent Dutch-roll mode was induced by the roll stability augmentation system at a high angle of attack, Mach 1.3 condition. The roll mode without roll stability augmentation was characterized by relatively large time constants. The HL-10 did not exhibit the roll-spiral mode coupling typical of lifting body configurations.

The vehicle responded to turbulence with a low-amplitude, high-frequency lateral mode due to the high effective dihedral. Because of this unique response, there was some pilot anxiety during the landing approach where turbulence was encountered. The pilots became less concerned as they acquired experience.

Three relatively serious problems were experienced on the first flight: an objectionable longitudinal control system limit cycle, an overly sensitive longitudinal stick, and intermittent flow separation over the upper aft portions of the vehicle. Modifications of the control system and the aerodynamic configuration of the tip fins precluded the recurrence of these problems.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., October 30, 1973

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TABLE 1. - PHYSICAL CHARACTERISTICS OF THE HL-10 LIFTING BODY VEHICLE

(a) Reference areas and lengths

Body -	
Reference planform area, m^2 (ft^2)	14.9 (160)
Length, m (ft)	6.45 (21.17)
Span, m (ft)	4.15 (13.60)
Aspect ratio, b^2/S	1.156
Elevons (two) -	
Area, each, m^2 (ft^2)	1.00 (10.72)
Span, each, m (ft)	1.09 (3.58)
Chord:	
Root, m (ft)	0.59 (1.93)
Tip, m (ft)	1.24 (4.06)
Elevon flap (two) -	
Area, each, m^2 (ft^2)	0.70 (7.50)
Span, each, m (ft)	1.09 (3.58)
Chord:	
Root, m (ft)	0.48 (1.58)
Tip, m (ft)	0.80 (2.63)
Vertical stabilizer -	
Area, m^2 (ft^2)	1.47 (15.80)
Height, m (ft)	1.53 (5.02)
Chord:	
Root, m (ft)	1.32 (4.32)
Tip, m (ft)	0.60 (1.97)
Leading-edge sweep, deg	25
Rudders (two) -	
Area, each, m^2 (ft^2)	0.41 (4.45)
Height, each, m (ft)	1.26 (4.12)
Chord, m (ft)	0.33 (1.08)
Outboard tip fin flaps (two) -	
Area, each, m^2 (ft^2)	0.35 (3.77)
Height at hinge line, m (ft)	1.37 (4.50)
Chord perpendicular to hinge line, m (ft)	0.76 (2.48)
Inboard tip fin flaps (two) -	
Area, m^2 (ft^2)	0.23 (2.48)
Height at hinge line, m (ft)	1.01 (3.31)
Chord perpendicular to hinge line, m (ft)	0.23 (0.75)

TABLE 1. - Concluded

(b) Typical mass, inertia, and center of gravity characteristics

Condition	m, kg (slugs)	I_X, kg-m (slug-ft^2)	I_Y, kg-m (slug-ft^2)	I_Z, kg-m (slug-ft^2)	I_{XZ}, kg-m (slug-ft^2)	ϵ, deg	Center of gravity location, cm (in.)		
							x	y	z
Maximum gross weight, full fuel	4544 (311.1)	2063 (1522)	8488 (6262)	9667 (7132)	752 (555)	5.6	342.9 (135.0)	0.51 (0.2)	10.4 (4.1)
Three-quarter fuel	4146 (284.1)	2006 (1480)	8329 (6145)	9459 (6979)	744 (549)	5.6	341.6 (134.5)	0.76 (0.3)	11.4 (4.5)
One-half fuel	3748 (256.8)	1948 (1437)	8169 (6027)	9252 (6826)	732 (540)	5.7	339.9 (133.8)	1.02 (0.4)	12.2 (4.8)
One-quarter fuel	3349 (299.5)	1889 (1394)	8005 (5906)	9041 (6670)	720 (531)	5.7	337.8 (133.0)	1.27 (0.5)	13.5 (5.3)
No fuel	2955 (202.5)	1862 (1374)	7818 (5768)	8839 (6521)	701 (517)	5.7	334.3 (131.6)	0.25 (0.1)	14.0 (5.5)
Glide flight, gear up	2937 (201.2)	1847 (1363)	7819 (5769)	8822 (6509)	705 (520)	5.7	334.3 (131.6)	0	14.2 (5.6)
Glide flight, gear down	2937 (201.2)	2110 (1557)	8010 (5910)	9051 (6678)	714 (527)	5.8	334.5 (131.5)	0	17.0 (6.7)
Landing	2816 (192.6)	1732 (1278)	7791 (5748)	8709 (6425)	712 (525)	5.8	335.0 (131.9)	-0.25 (-0.1)	14.2 (5.6)

TABLE 2. - SECONDARY CONTROL FLAP POSITIONS FOR THE BASIC SUBSONIC AND TRANSONIC CONFIGURATIONS OF THE HL-10 LIFTING BODY VEHICLE

Configuration	Elevon flaps, deg up from elevon	Speed brake, deg outboard from faired position	Tip fin flaps, deg from faired position	
			Inboard	Outboard
Subsonic -				
Original	0	0	0	0
Final	5	0	3	3
Transonic	30	8	32.5	30

TABLE 3.- PILOT STICK, CONTROL SURFACE, AND RUDDER PEDAL CHARACTERISTICS

Flight	Pilot longitudinal stick authority, cm (in.)	Pilot elevon authority, deg	Pilot longitudinal stick force gradient, N/cm (lb/in.)	Elevon gearing, deg/cm (deg/in.)	Pilot lateral stick authority, cm (in.)	Pilot lateral stick force gradient, N/cm (lb/in.)	Pilot aileron authority, deg	Aileron gearing, deg/cm (deg/in.)	Pilot rudder pedal authority, cm (in.)	Pilot rudder pedal force gradient, N/cm (lb/in.)	Pilot rudder authority, deg	Rudder gearing, deg/cm (deg/in.)
1	-7.62 (-3) 15.22 (6)	36.2 to -26	14.7 (8.4)	2.73 (6.92)	±7.44 (±2.93)	4.80 (2.74)	±12.5	1.68 (4.27)	±7.27 (±3.1)	24.02 (13.72)	±10.25	1.3 (3.41)
2, 3	-9.91 (-3.9) 13.20 (5.2)	10 to -25		1.51 (3.75)	±6.73 (±2.65)		±19.2	2.86 (7.25)				
4, 5	-9.91 (-3.9) 13.20 (5.2)	10 to -25		1.51 (3.75)	±7.11 (±2.80)		±12.1	1.70 (4.32)				
6 to 9	-9.65 (-38) 13.70 (5.4)	3.8 to -26		1.27 (3.24)	±7.11 (±2.80)		±12.1	1.70 (4.32)				
10 to 37	-9.91 (13.9) 13.46 (5.3)	13.2 to 23.7		Nonlinear (see fig. 12)	±10.29 (±4.05)		±17.3	1.68 (4.27)				

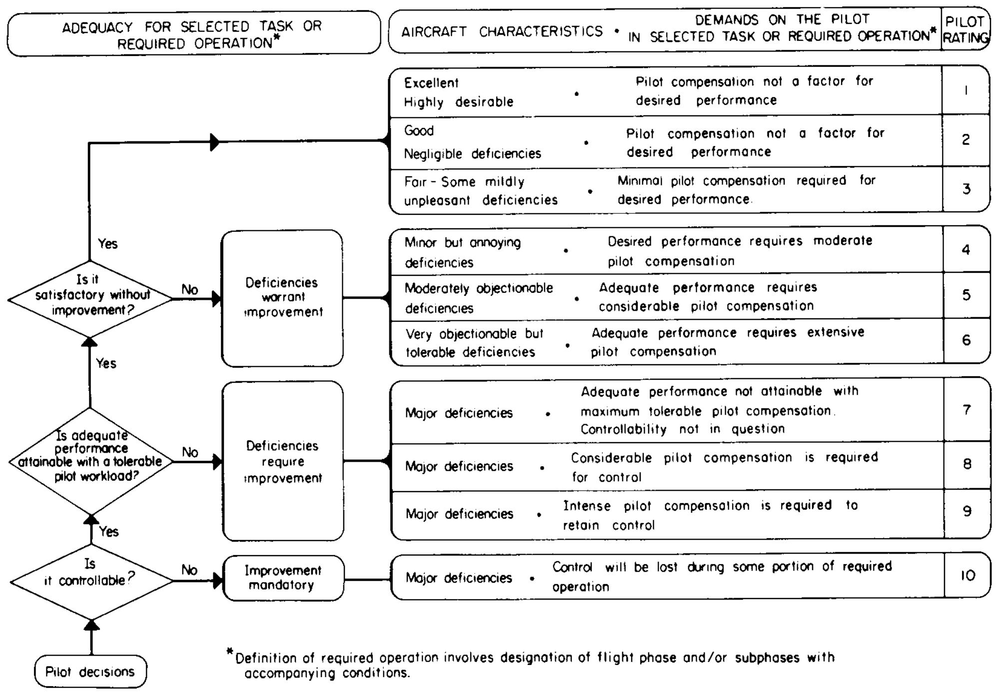
TABLE 4. - SUMMARY OF THE 37 FLIGHTS OF THE HL-10 LIFTING BODY VEHICLE

Type of flight	Number of flights	Maximum Mach number	Maximum altitude, m (ft)	Remarks
Glide	5	0.71	13,700 (45,000)	Pilot's first flight (pilot checkout).
	8	0.71	13,700 (45,000)	Verification of subsonic configuration and transonic configuration launch. With flap transition.
	2	--	13,700 (45,000)	Powered approach investigation (landing-rocket-powered).
Powered	1	0.67	13,700 (45,000)	First powered flight. Alternate site landing.
	9	1.54	23,100 (75,600)	Envelope expansion verification of transonic configuration and its handling qualities.
	12	1.86	27,500 (90,000)	Acquisition of aerodynamic and stability and control data. Performance and handling quality evaluations.

TABLE 5.- MODIFIED COOPER-HARPER HANDLING QUALITIES RATING SCALE

AND MILITARY SPECIFICATION DEFINITION OF FLYING QUALITIES LEVELS

(a) Cooper-Harper rating scale (from ref. 5)



*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

(b) Military Specification's definition of levels of flying qualities (from ref. 6)

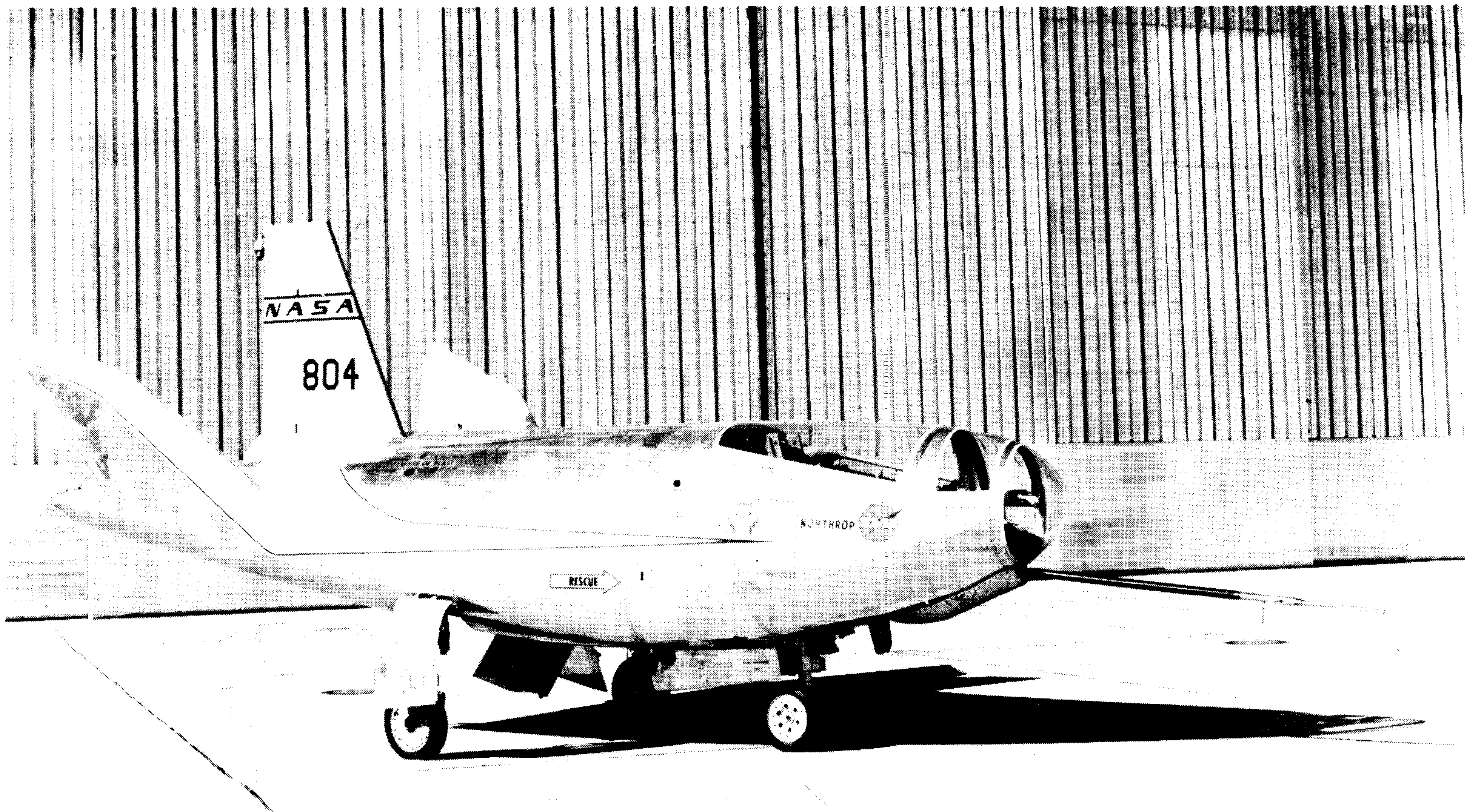
Level 1	Flying qualities clearly adequate for the mission flight phase.
Level 2	Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.
Level 3	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both.

TABLE 6.- SELECTED LONGITUDINAL RESPONSE CHARACTERISTICS AND PILOT RATINGS OF THE HL-10 LIFTING BODY VEHICLE

Task	Configuration	Pilot rating	M	$\bar{q}$, N/m^2 (lb/ft^2)	α, deg	K_q, deg/deg/sec	ω_{sp}, rad/sec	ω_{sp}, Hz	ζ_{sp}	τ_{sp_1}, sec	τ_{sp_2}, sec	a_n/α, g/rad
Longitudinal control at landing	Subsonic	2 to 2.5	0.42	9863.3 (206)	15	0.3	----	-----	-----	0.322	0.093	6.73
Longitudinal control at constant angle of attack	Transonic	4.0	0.95	7900.2 (165)	11	0.4	----	-----	-----	0.291	0.131	5.35
Low angle of attack evaluation	Transonic	4.0	1.00	4548.6 (95)	6	0.4	4.74	0.754	0.662	-----	-----	2.39
Constant angle of attack acceleration	Transonic	2.5	1.20	6703.2 (140)	8.5	0.1	5.18	0.824	0.206	-----	-----	2.29
Stability and control evaluation	Transonic	2.5	0.85	4788.0 (100)	19	0.4	----	-----	-----	0.346	0.297	3.40
		2.5	0.85	4788.0 (100)	25	0.4	----	-----	-----	0.481	0.261	3.37
		2.5	0.85	4788.0 (100)	8	0.4	3.70	0.590	0.973	-----	-----	3.35
		3.0	1.10	7182.0 (150)	11	0.4	5.24	0.833	0.815	-----	-----	3.40
		3.5	0.98	7660.8 (160)	14	0.4	5.56	0.885	0.954	-----	-----	4.94
		5.0	0.85	8379.1 (175)	12	0	4.49	0.715	0.134	-----	-----	5.77
Configuration transition	Transonic	4.0	0.60	9097.3 (190)	15	0	4.32	0.687	0.156	-----	-----	6.40
	Subsonic	4.0	0.60	9097.3 (190)	15	0	4.01	0.638	0.174	-----	-----	7.75

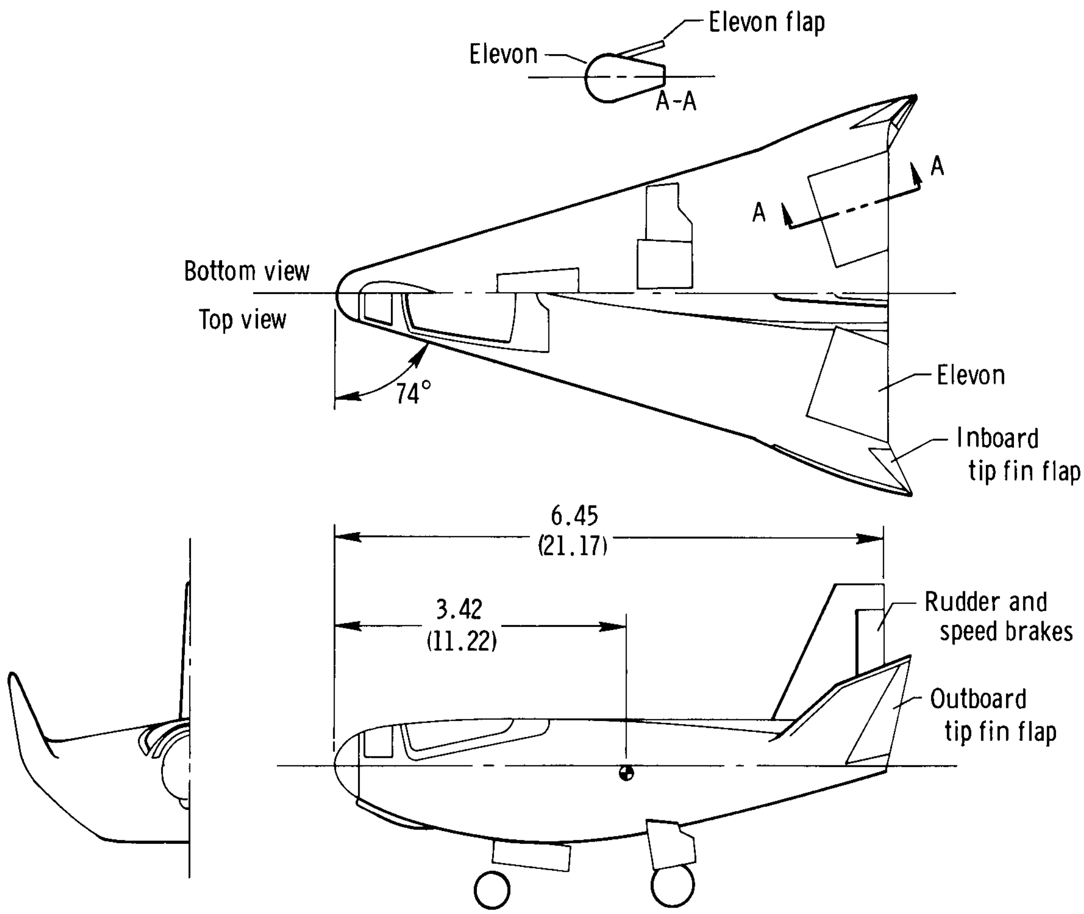
TABLE 7. - SELECTED LATERAL-DIRECTIONAL RESPONSE CHARACTERISTICS AND PILOT RATINGS OF THE HL-10 LIFTING BODY VEHICLE

Task	Configuration	Pilot rating	M	$\bar{q}$, N/m^2 (lb/ft^2)	α, deg	K_p', deg/deg/sec	K_r', deg/deg/sec	ω_d', rad/sec	ζ_d	φ/β	τ_r', sec	$L_{\delta_a}\delta_a$', rad/sec^2
Roll control and bank angle evaluation	Transonic	1.0	0.81	6,224.4 (130)	18	0.4	0.2	4.57	0.220	2.02	0.25	3.34
		2.0	0.84	6,176.6 (129)	18	0	0.4	4.80	0.094	2.38	1.27	3.16
		2.5	0.85	5,793.5 (121)	17.4	0	0.2	4.60	0.070	2.39	2.42	3.00
Stability and control evaluation	Transonic	3.0	0.66	10,054.9 (210)	20	0.3	0.4	6.41	0.261	2.14	0.22	4.19
		3.5	0.64	8,857.9 (185)	14.3	0	0.4	5.43	0.164	2.74	0.74	4.85
		3.5	0.71	7,182.0 (150)	17.5	0	0.4	4.93	0.108	2.61	0.85	3.30
		4.0	1.15	3,351.6 (70)	7.5	0.1	0.1	2.93	0.154	3.52	2.02	2.54
		4.0	0.82	8,139.6 (170)	14	0	0.2	5.13	0.109	2.52	1.56	4.64
		4.0 to 5.0	0.70	6,751.1 (141)	16.2	0	0.2	4.69	0.089	2.71	1.85	3.40
		5.0	0.75	9,815.5 (205)	13.5	0	0	5.66	0.075	2.63	2.70	5.32
		5.5 to 6	0.73	6,368.1 (133)	17.3	0	0	4.74	0.055	2.60	10.40	3.01
	Subsonic	4.0	0.65	7,421.4 (155)	15	0	0.4	4.24	0.188	2.35	0.76	4.97
Control sensitivity and stability	Subsonic	4.5 to 5.0	0.55	8,618.5 (180)	14.5	0	0	4.81	0.081	2.64	2.12	4.10
		5.0	0.60	10,054.9 (210)	13	0	0	5.29	0.071	3.14	3.73	6.30



(a) One-quarter front view. E-18261

Figure 1. HL-10 lifting body vehicle.



(b) Three-view drawing. Dimensions in meters (feet) except where noted otherwise.

Figure 1. Concluded.

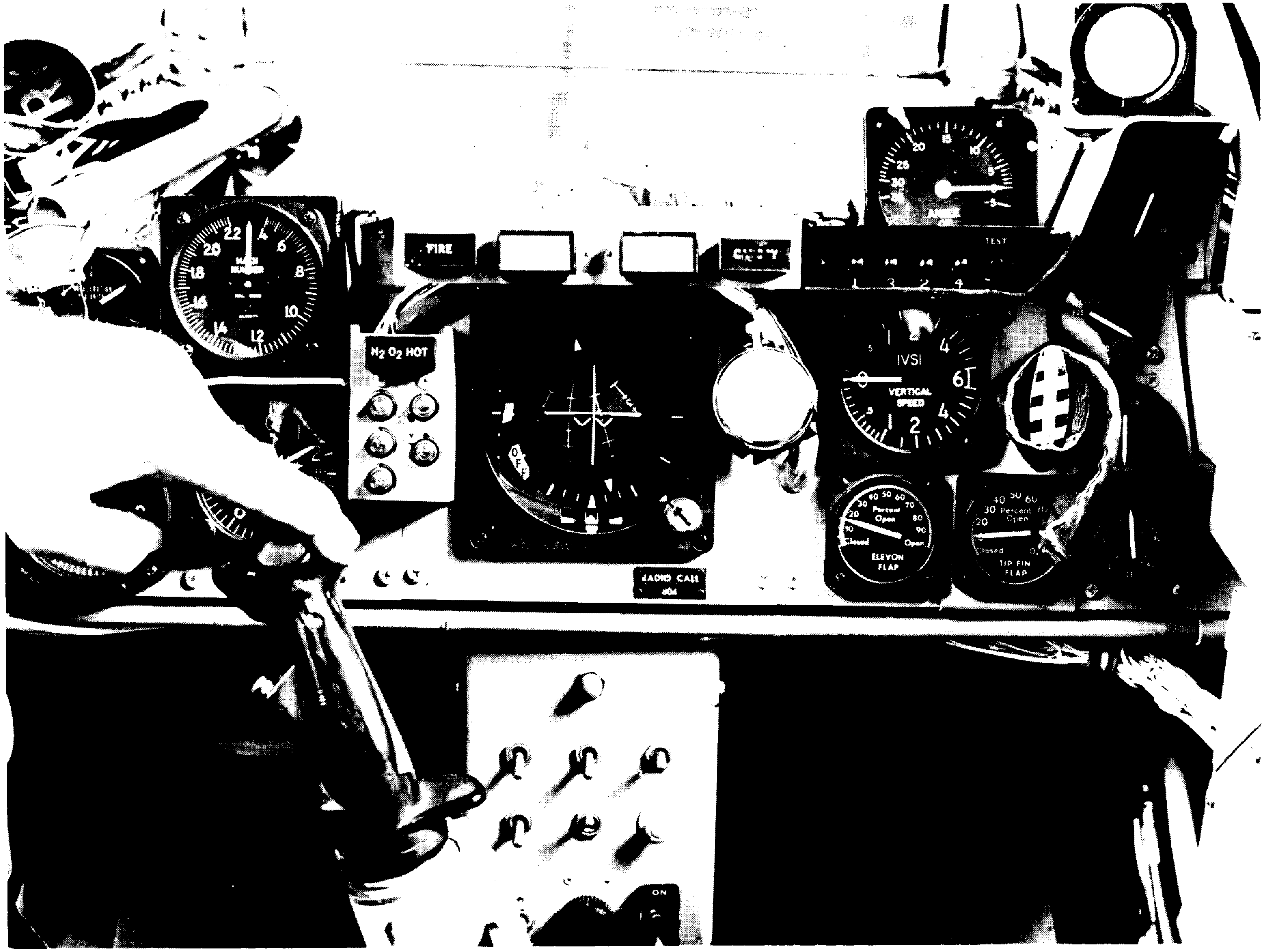
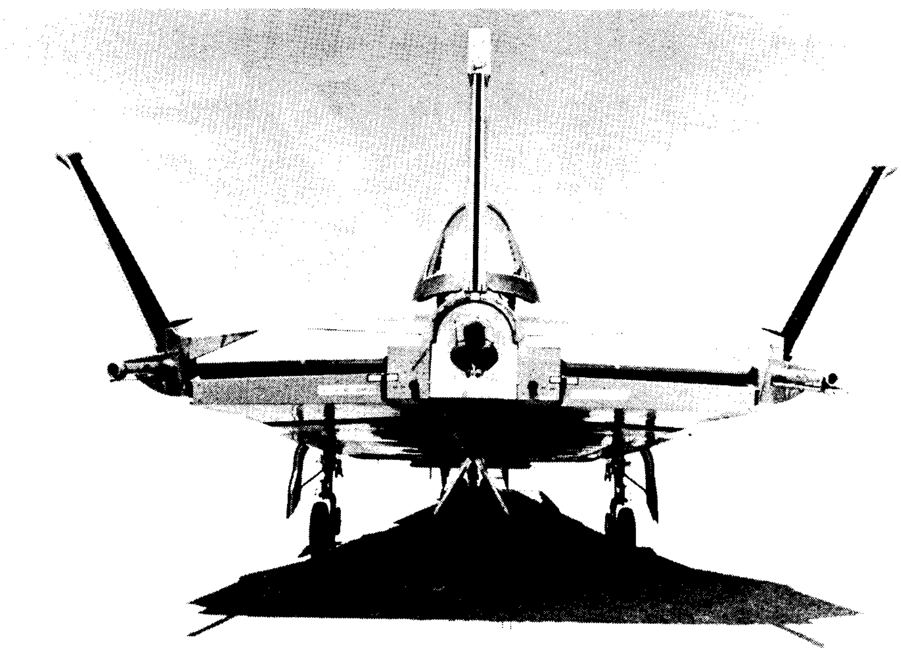
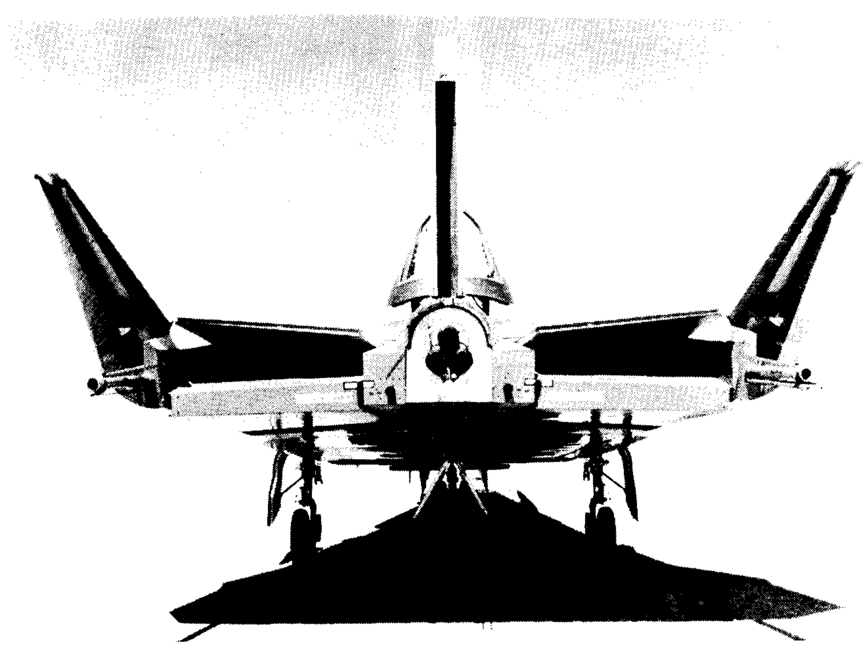


Figure 2. Instrument panel arrangement. E-20304



(a) Subsonic flap position. E-21537



(b) Transonic flap position. E-21536

Figure 3. HL-10 lifting body vehicle.

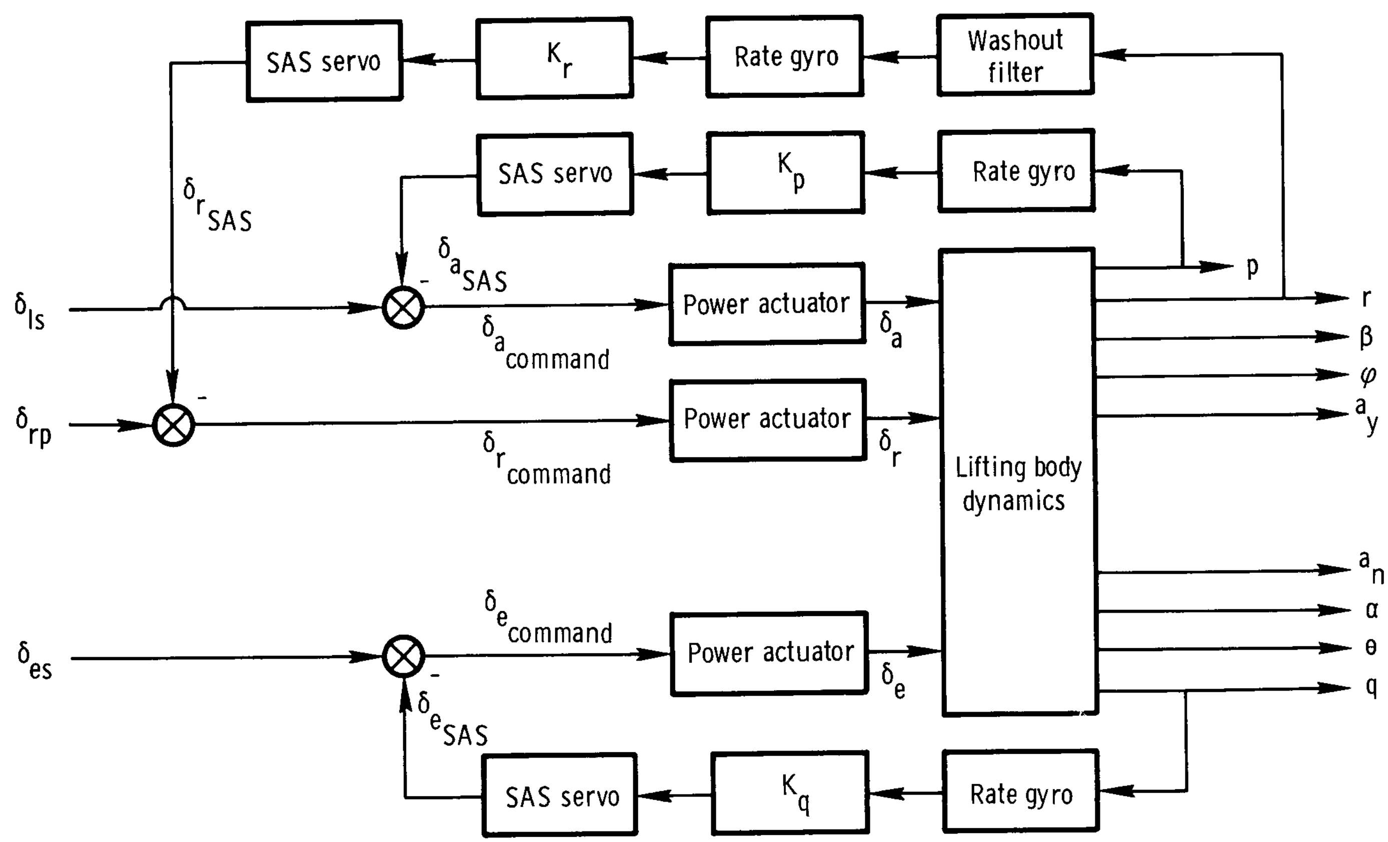


Figure 4. Conceptual block diagram of flight control system.

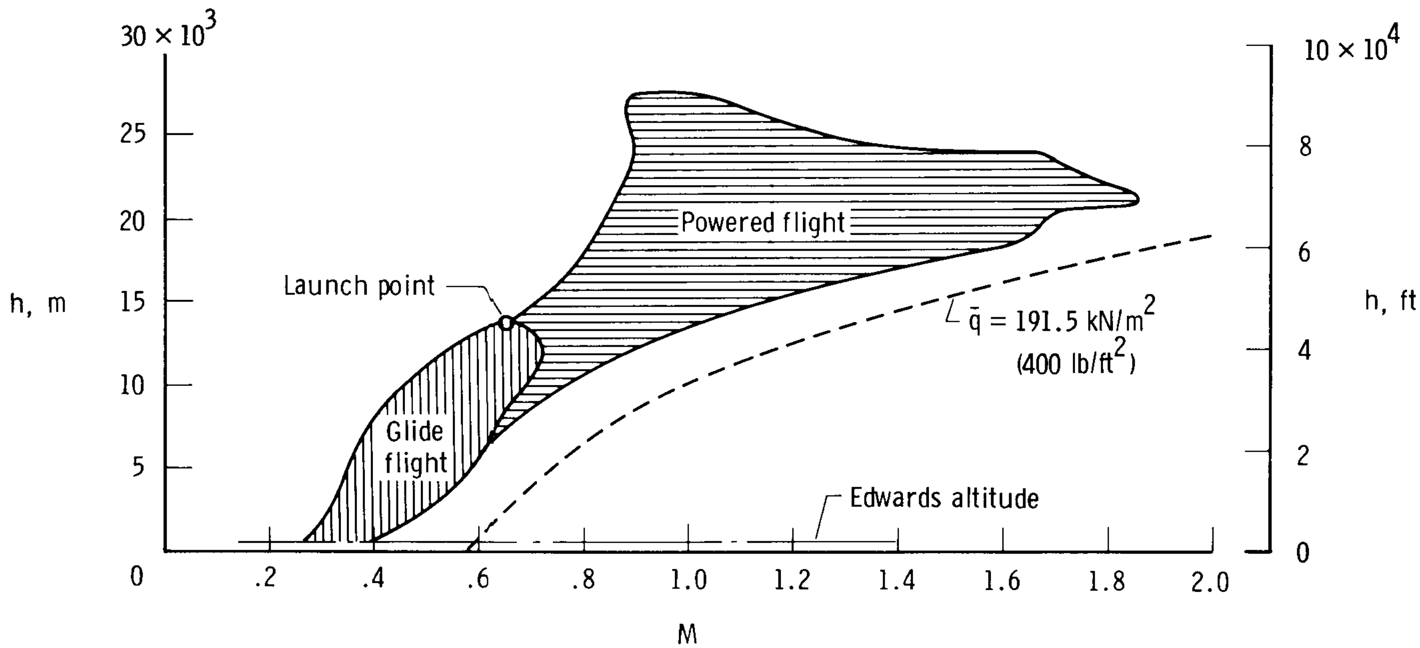


Figure 5. Approximate altitude and Mach number envelope.

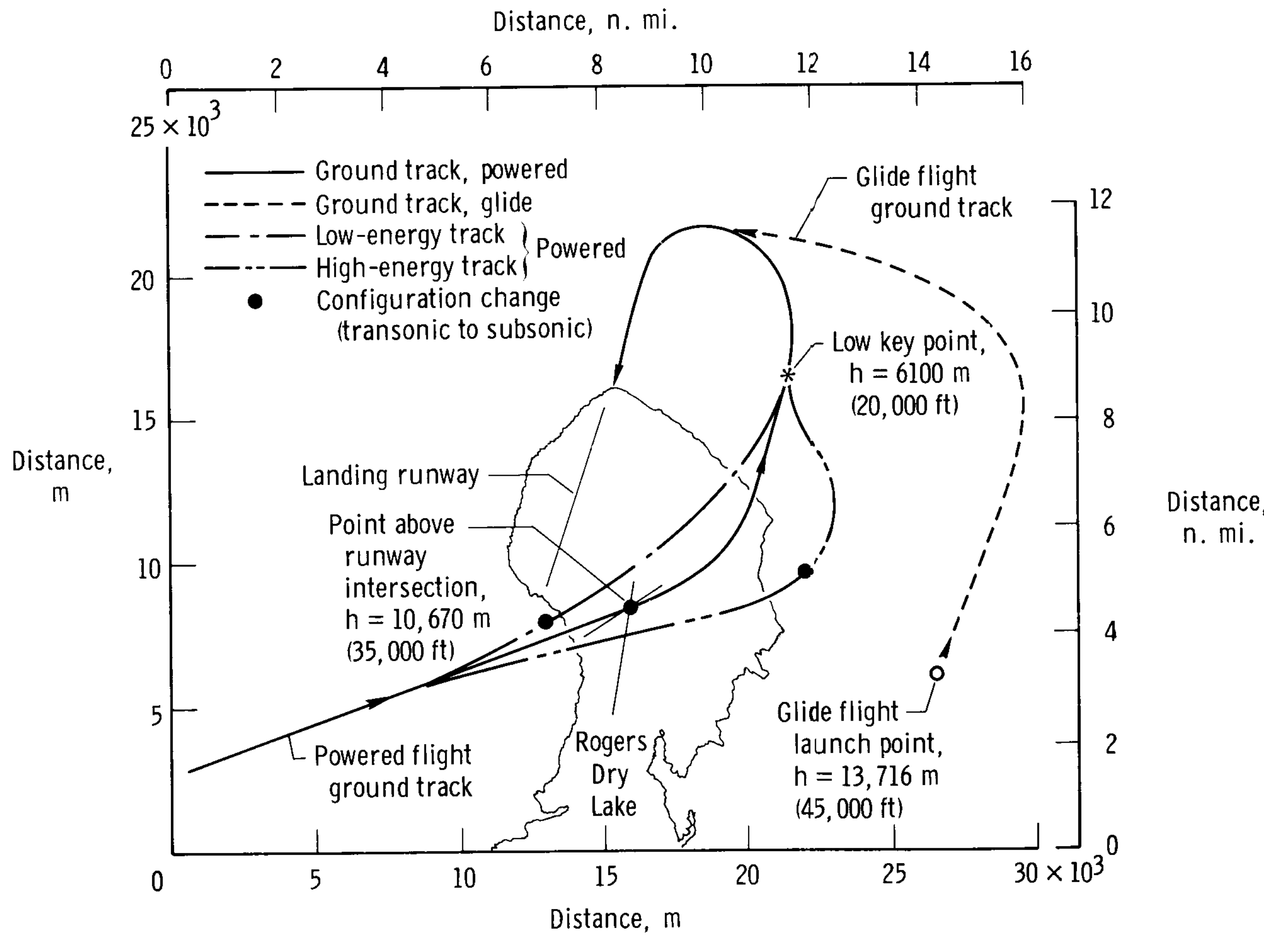


Figure 6. Typical flight ground track for the terminal approach and landing pattern.

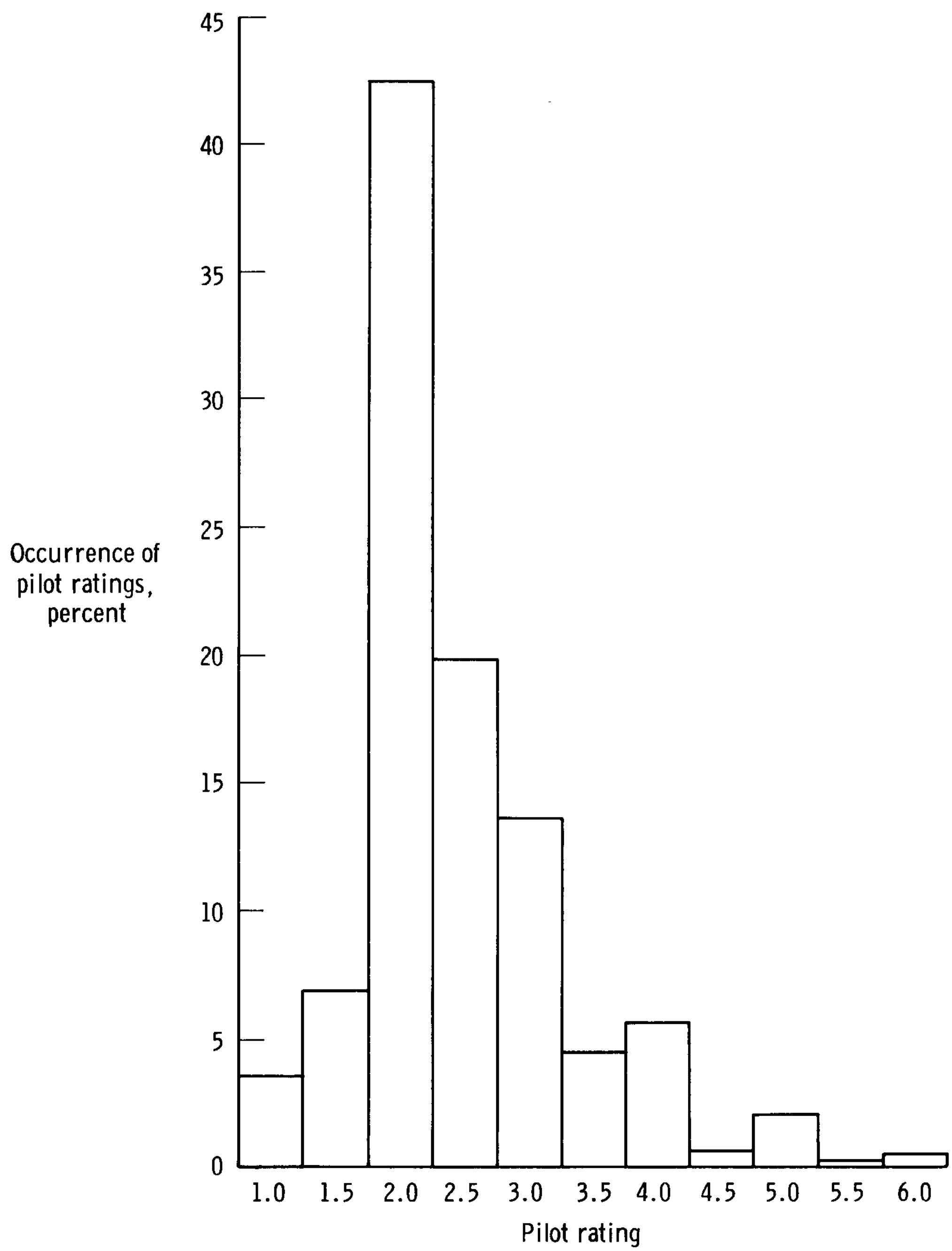
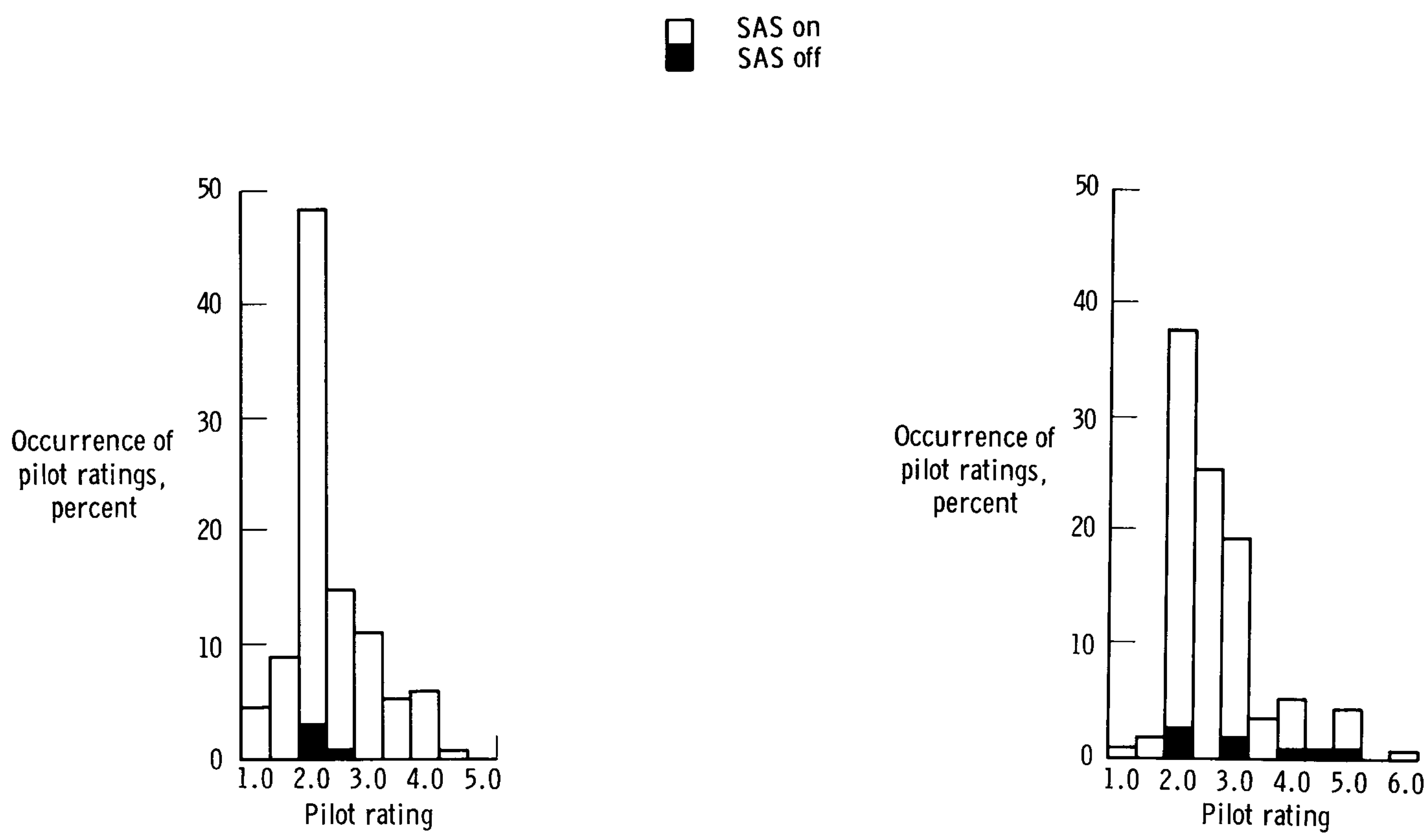


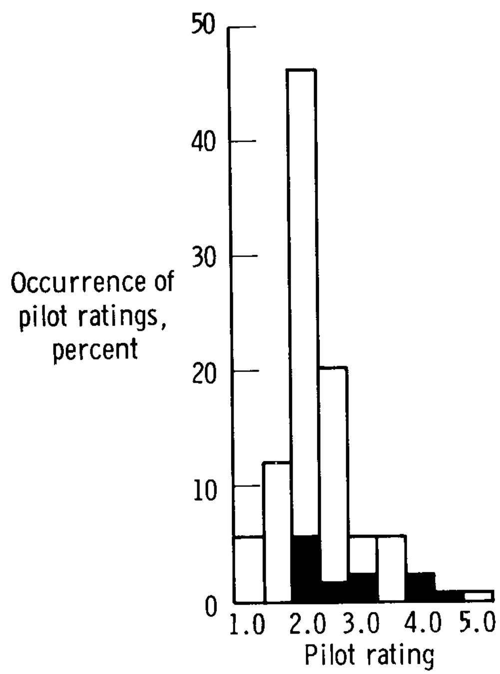
Figure 7. Percentage distribution of Cooper-Harper pilot ratings obtained during 37 flights. Total ratings, 419.



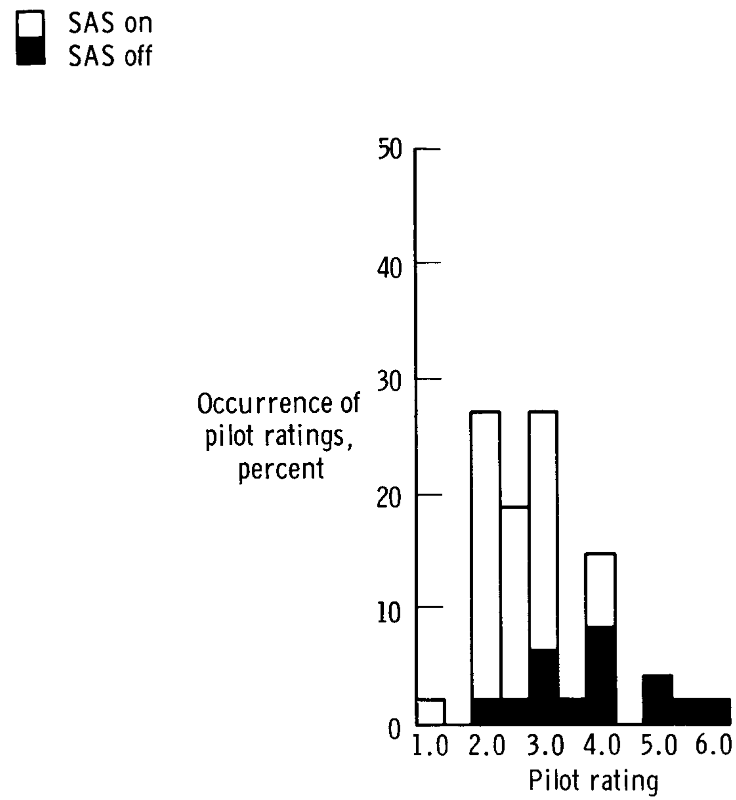
(a) Subsonic configuration. SAS on, 129 ratings (96.3 percent); SAS off, 5 ratings (3.7 percent); total ratings, 134.

(b) Transonic configuration. SAS on, 106 ratings (93 percent); SAS off, 8 ratings (7 percent); total ratings, 114.

Figure 8. Percentage distribution of longitudinal Cooper-Harper pilot ratings for the subsonic and transonic configurations, SAS on and off. Total ratings, 248.



(a) Subsonic configuration. SAS on, 107 ratings (87 percent); SAS off, 16 ratings (13 percent); total ratings, 123.



(b) Transonic configuration. SAS on, 34 ratings (70.8 percent); SAS off, 14 ratings (29.2 percent); total ratings, 48.

Figure 9. Percentage distribution of lateral-directional Cooper-Harper pilot ratings for the subsonic and transonic configuration, SAS on and off. Total ratings, 171.

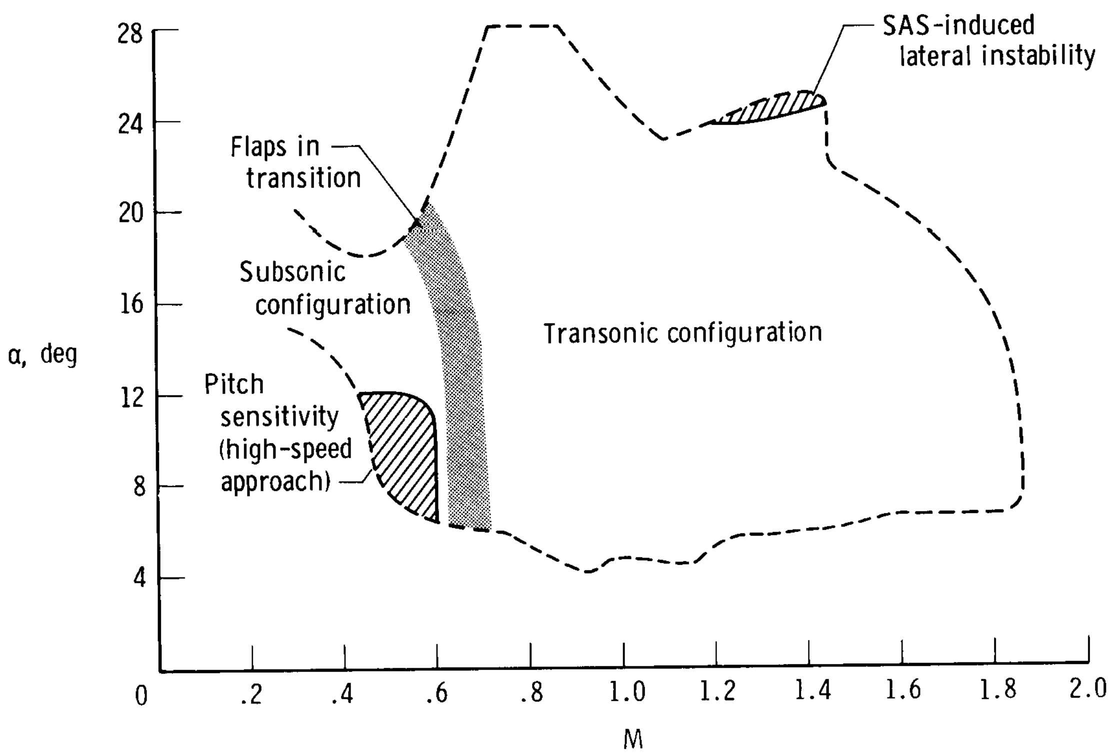


Figure 10. Flight envelope in terms of angle of attack and Mach number.

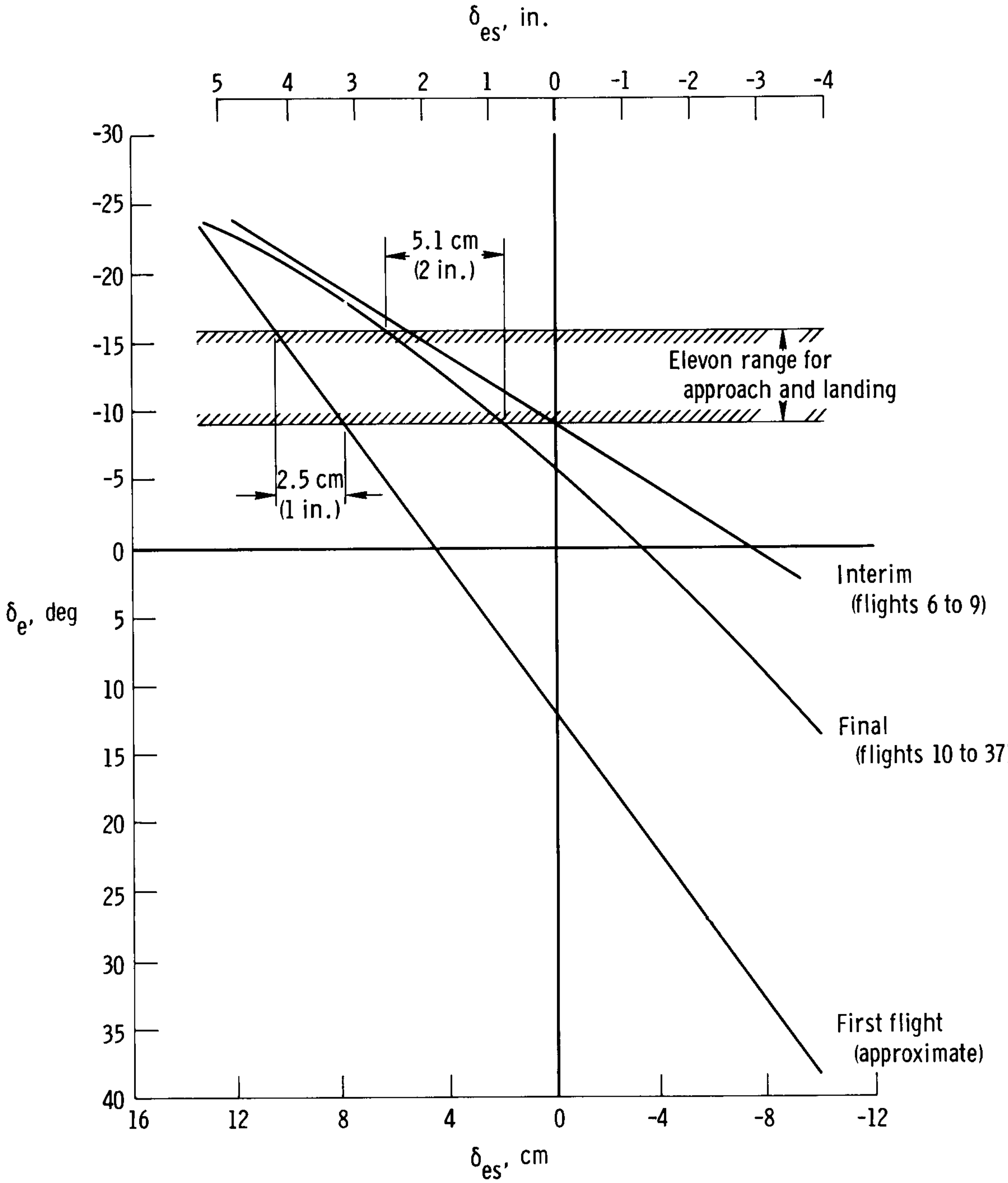


Figure 11. Elevon gearing used during flight tests.

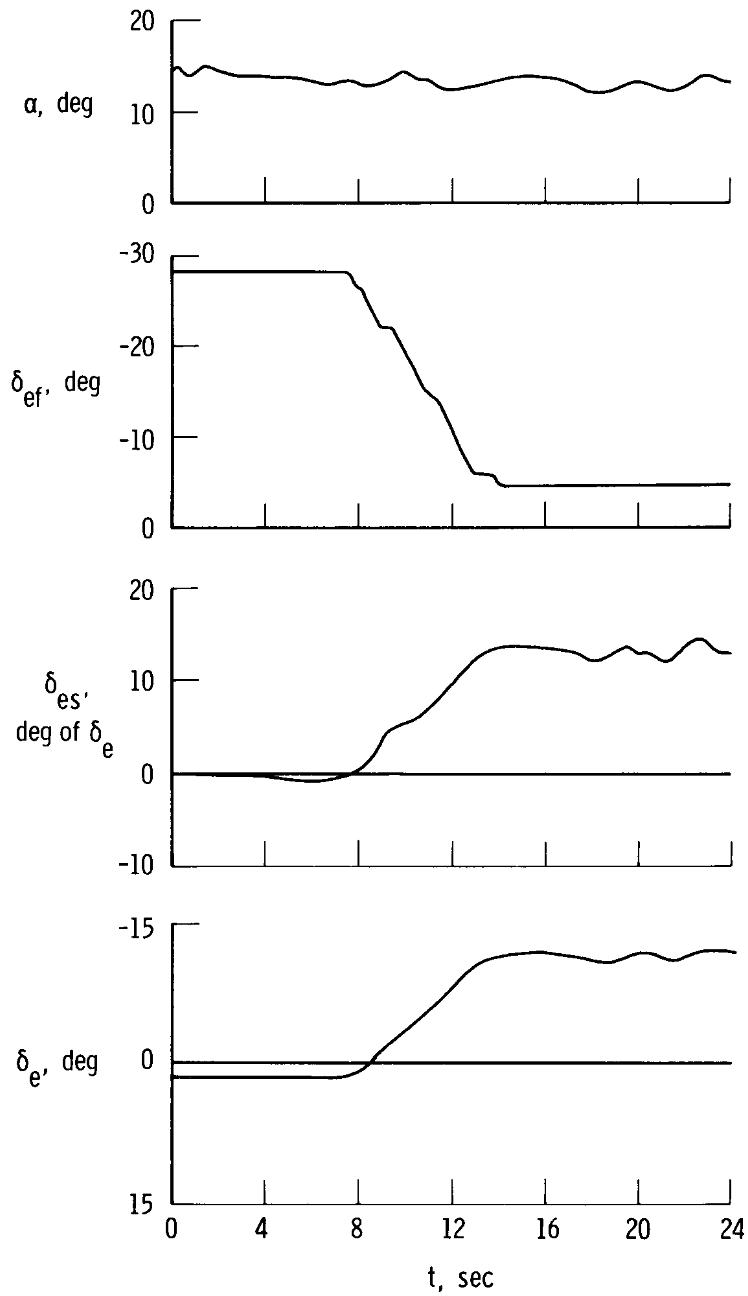


Figure 12. Angle of attack during flap position change. M = 0.65; $\bar{q}$ = 8150 N/m^2 (170 lb/ft^2); V = 195 m/sec (640 ft/sec); K_q = 0.4 deg/deg/sec.

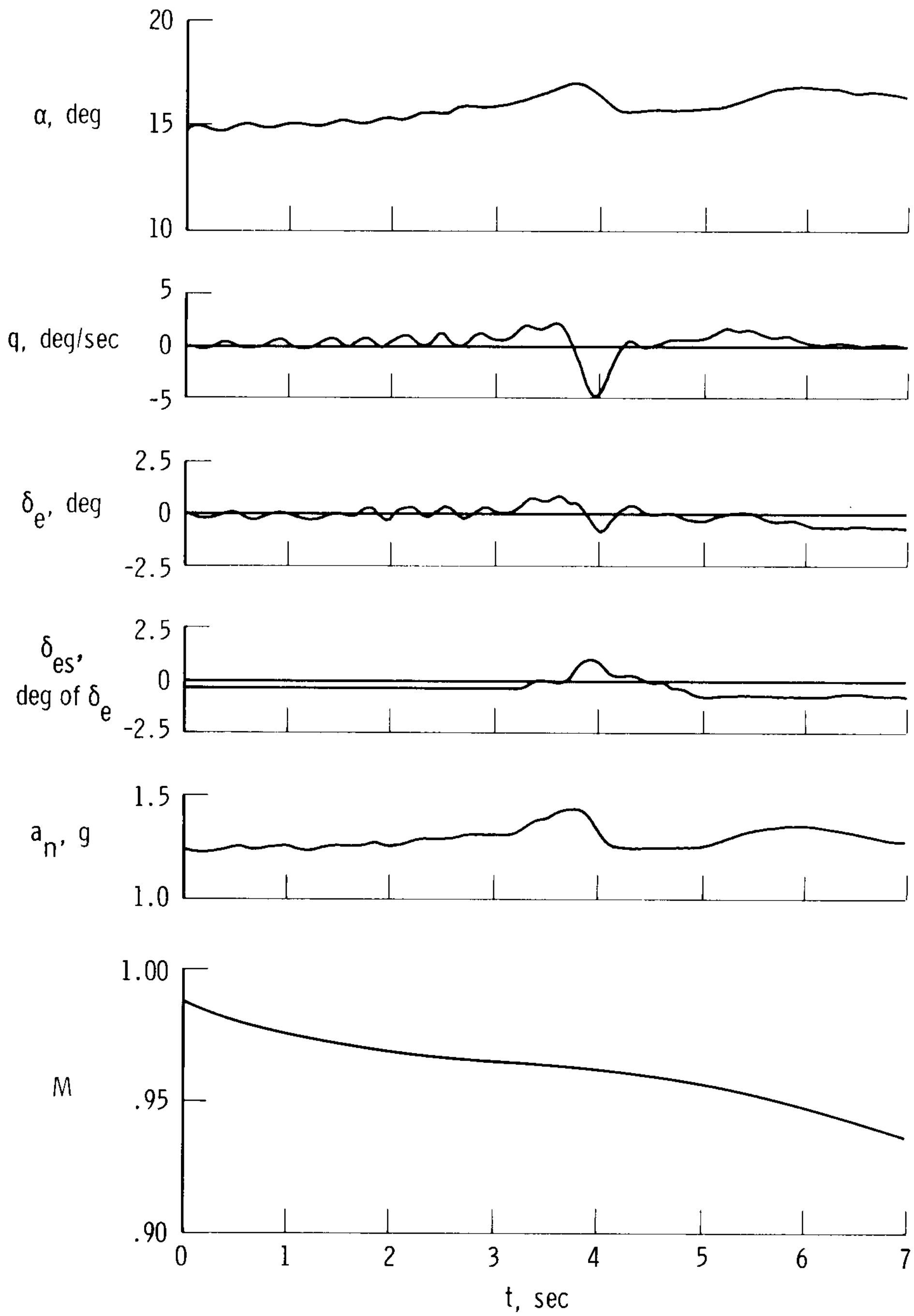


Figure 13. Time history of aerodynamic pitchup trim change experienced while decelerating through the transonic speed range. $\bar{q} \approx 9193$ N/m^2 (192 lb/ft^2); $K_p = 0.3$ deg/deg/sec; $K_q = 0.4$ deg/deg/sec; $K_r = 0.2$ deg/deg/sec.

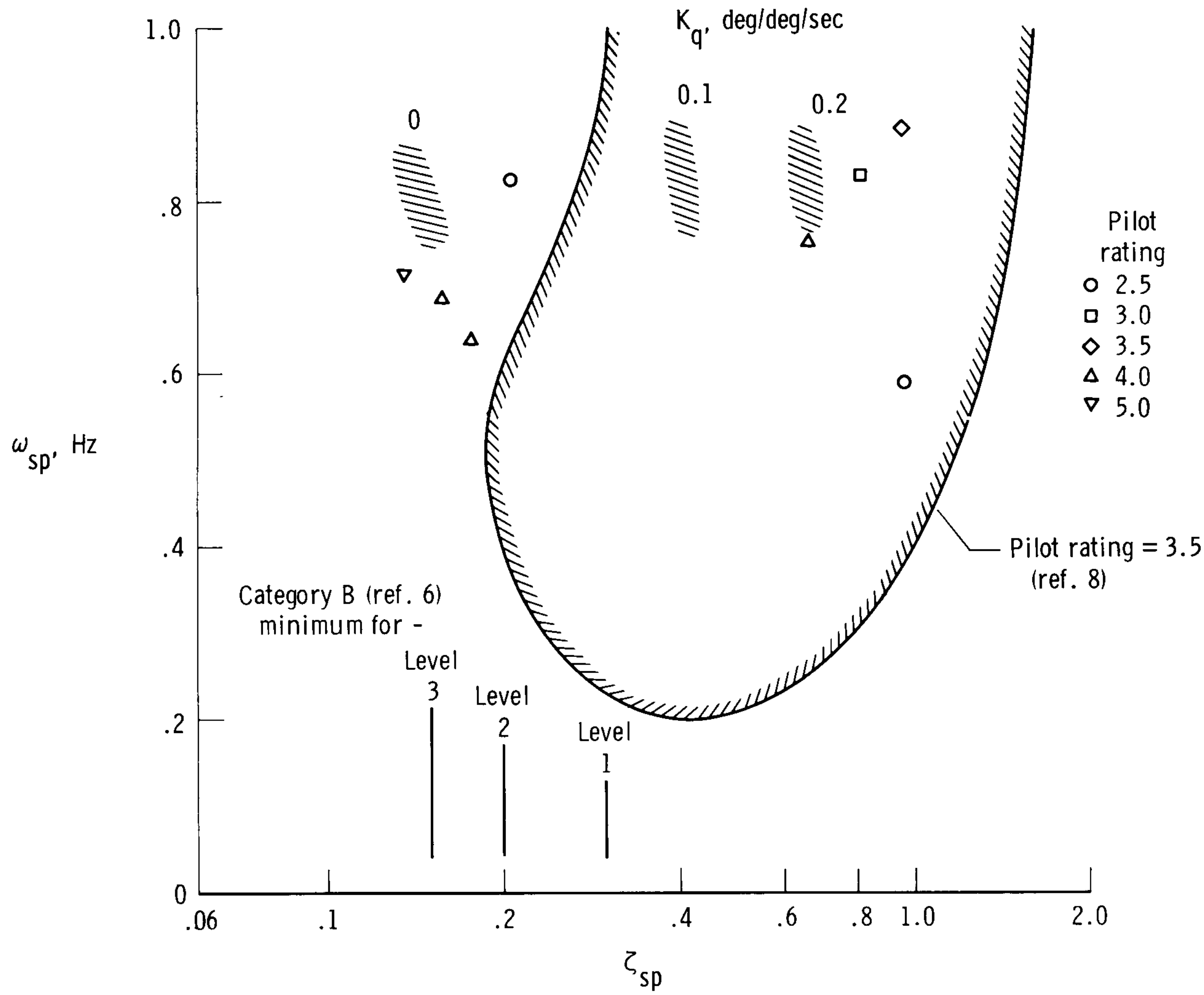


Figure 14. Flight-determined longitudinal short-period mode characteristics. M = 0.4 to 1.2; $\alpha = 6^\circ$ to 20°; K_q = 0 to 0.4 deg/deg/sec; hashed area represents $\alpha = 8^\circ$ to 20° where M = 0.77, $\bar{q}$ = 9540 N/m^2 (199 lb/ft^2), V = 227 m/sec (744 ft/sec), transonic configuration.

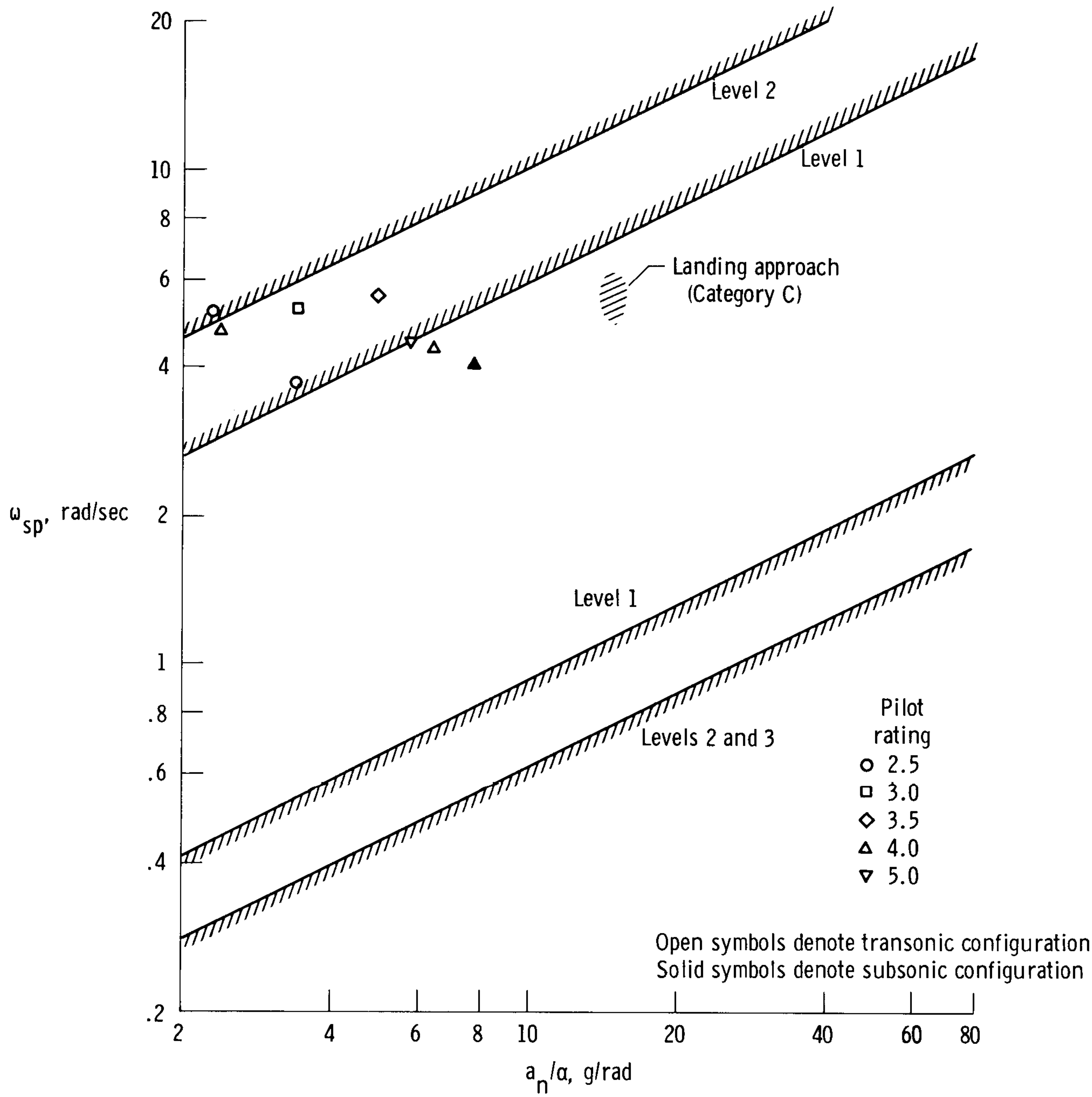


Figure 15. Comparison of HL-10 longitudinal short-period mode frequency and acceleration sensitivity characteristics with reference 6 requirements. Category B flight phases (except as noted); M = 0.4 to 1.2; $\alpha = 6^\circ$ to 20°; K_q = 0 to 0.4 deg/deg/sec.

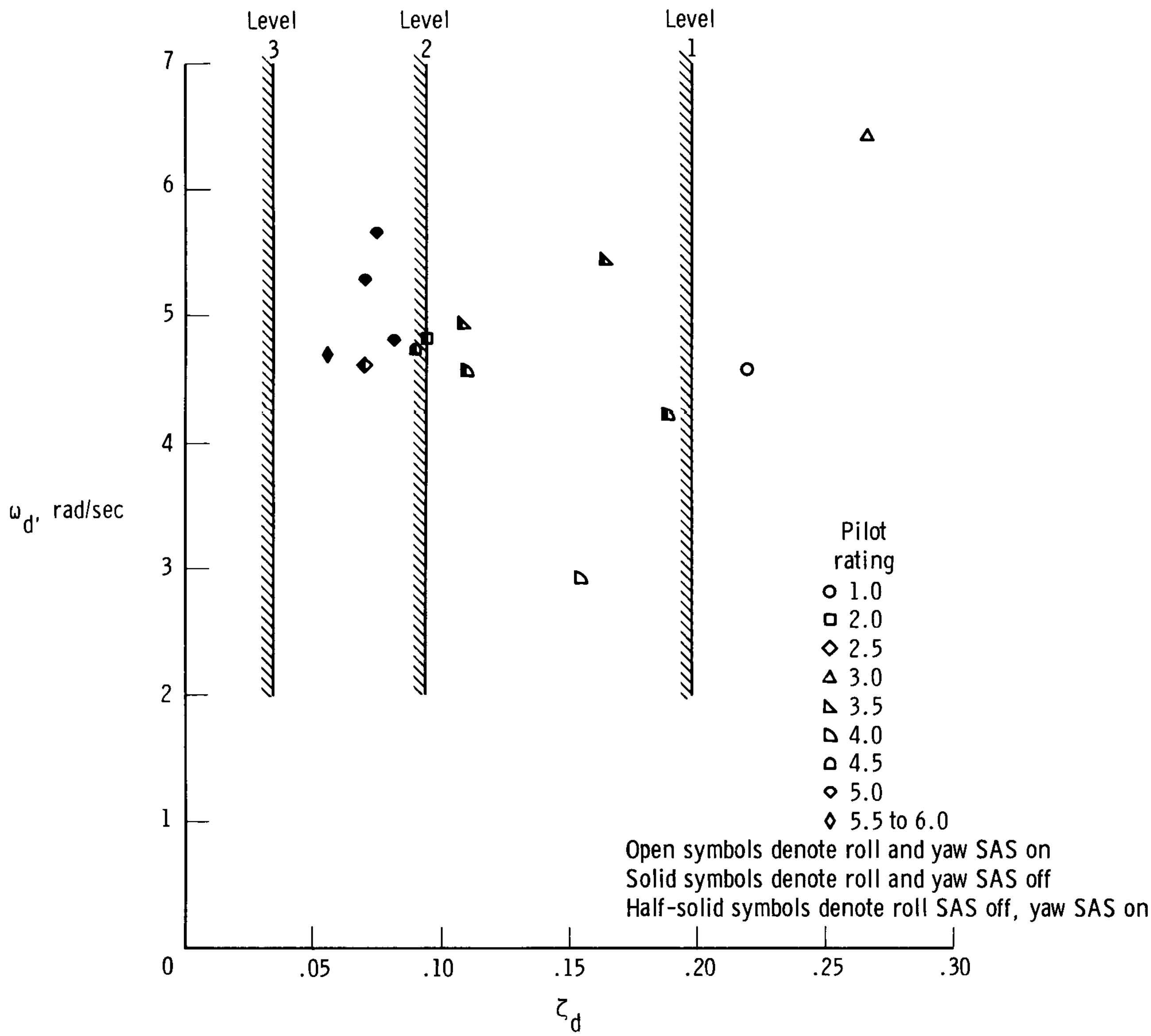


Figure 16. Comparison of HL-10 Dutch-roll mode with Dutch-roll mode criteria of reference 6 for class II aircraft. $\omega_d^2 |\varphi/\beta|_d > 20$ (rad/sec)^2.

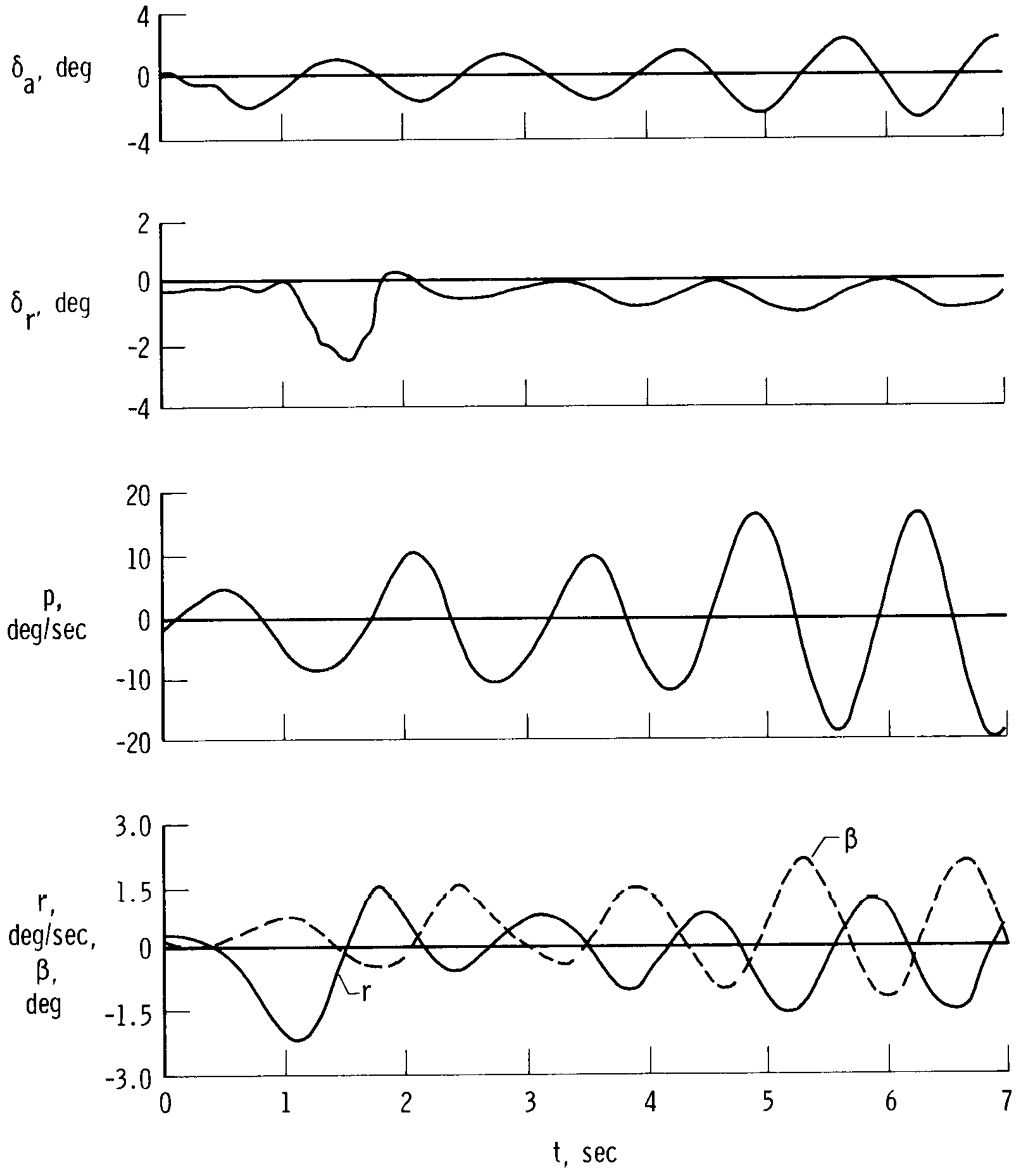


Figure 17. Dutch-roll mode instability at $M = 1.3$, $\alpha = 24.4°$, $\bar{q} = 4979.6 \ N/m^2$ ($104 \ lb/ft^2$), $\theta = -17.3°$, $V = 381.9$ m/sec (1253 ft/sec), $K_p = 0.1$ deg/deg/sec, $K_r = 0.4$ deg/deg/sec.

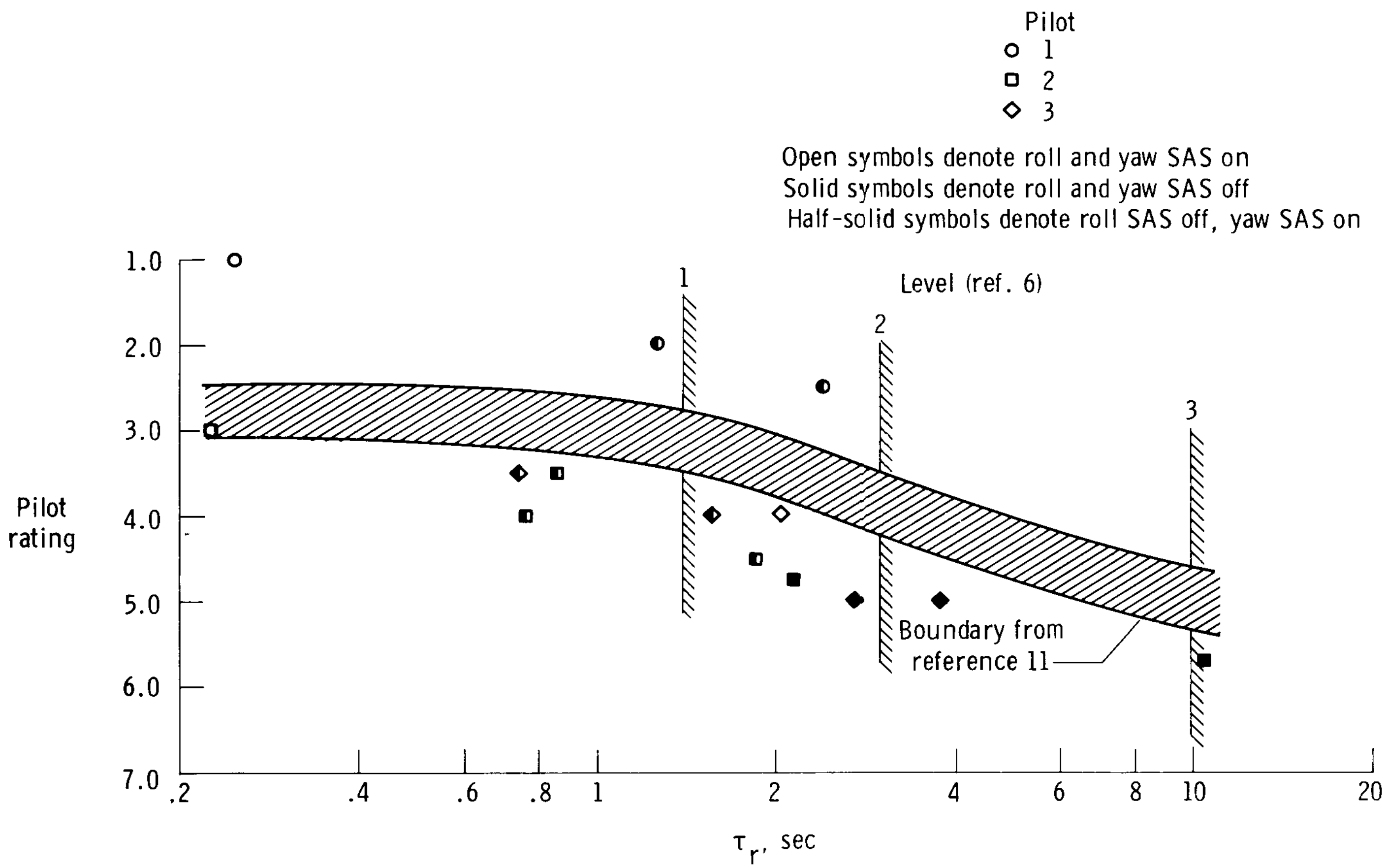


Figure 18. Comparison of pilot ratings of HL-10 roll mode time constant with roll mode criteria from references 6 and 11.

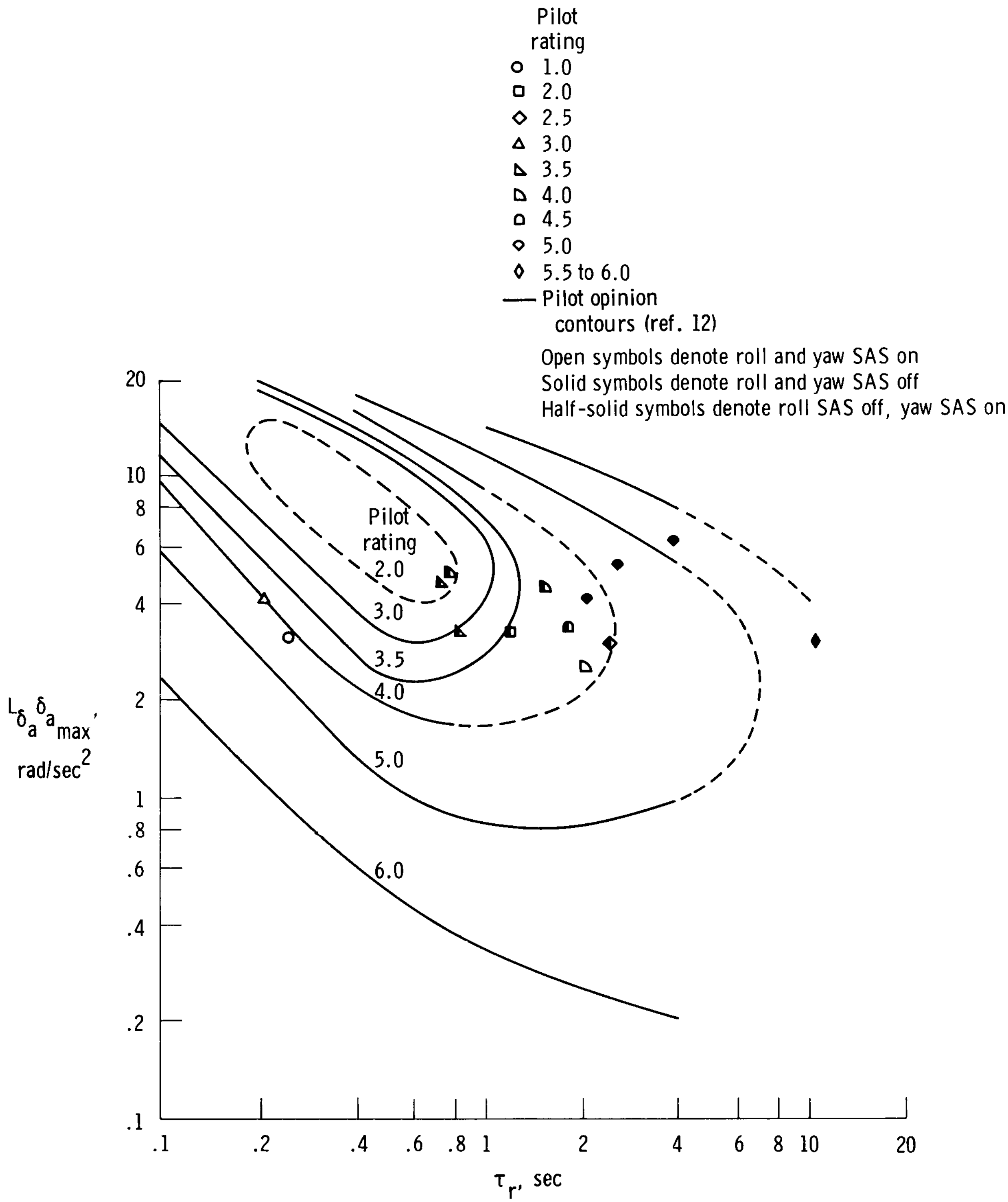


Figure 19. Comparison of HL-10 in-flight lateral axis pilot evaluations with roll-simulator-derived pilot opinion contours from reference 12.

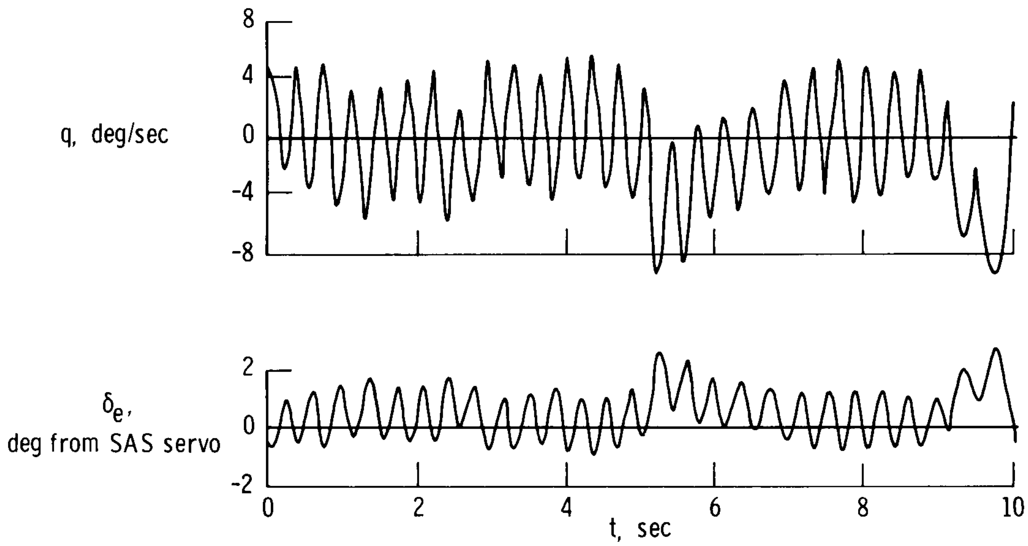


Figure 20. Longitudinal control system limit-cycle characteristics during the first flight. $\bar{q} = 14,360\ N/m^2$ (300 lb/ft^2); $K_q = 0.3$ deg/deg/sec.

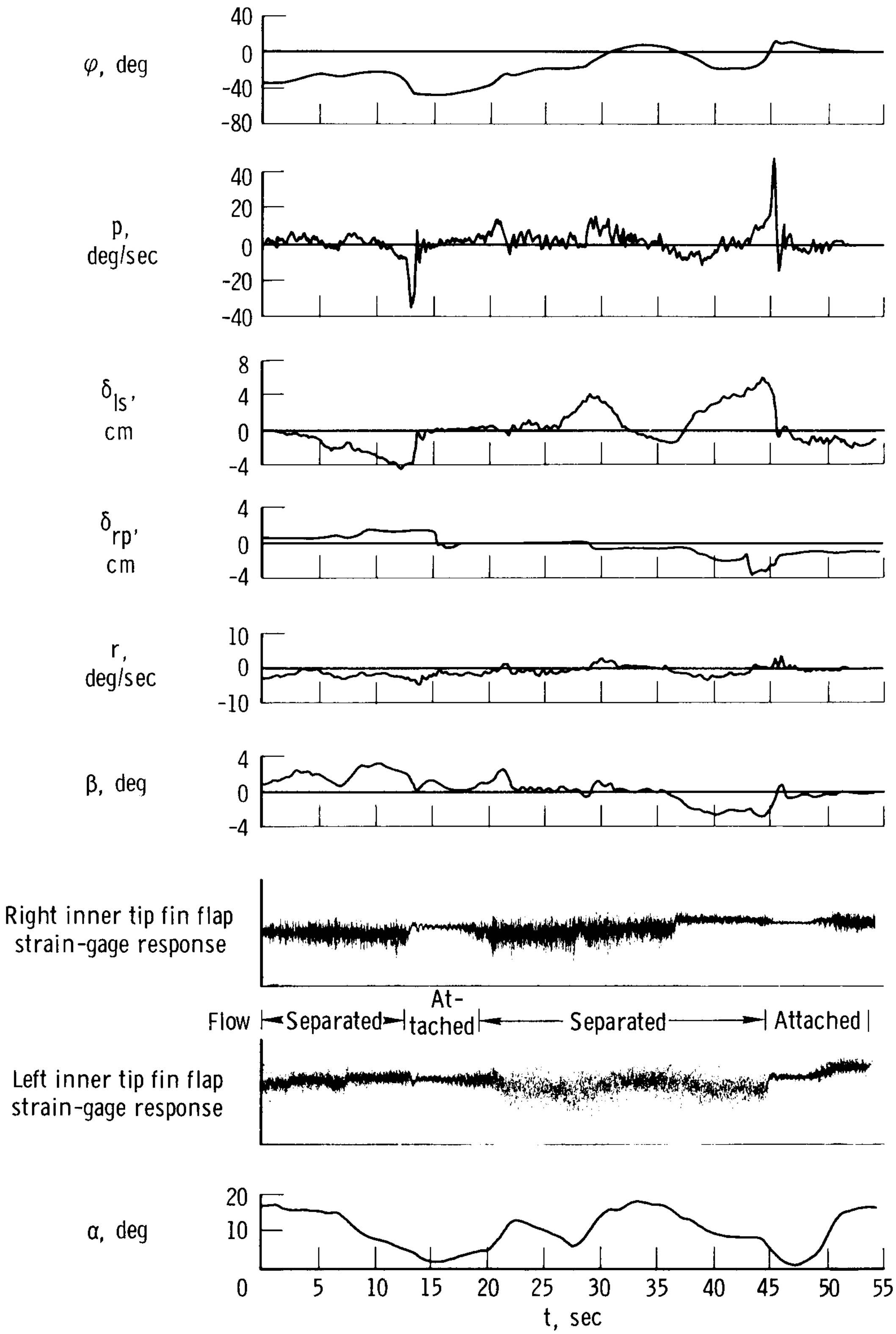


Figure 21. Time history of first flight showing flow separation and reattachment. Time begins approximately 49.3 seconds after launch.

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